5
PLASMA IMMERSION ION IMPLANTATION APPARATUS INCLUDING AN INDUCTIVELY COUPLED PLASMA SOURCE HAVING LOW DISSOCIATION AND LOW MINIMUM PLASMA VOLTAGE

10
Inventors:
Kenneth S. Collins, Hiroji Hanawa, Kartik Ramaswamy, Andrew Nguyen, Amir Al-Bayati, Biagio Gallo, and Gonzalo Antonio Monroy

15

CROSS-REFERENCE TO RELATED APPLICATIONS
20   This application is a continuation-in-part of U.S. Application Serial No. 10/164,327 filed June 5, 2003 by Kenneth Collins et al., entitled EXTERNALLY EXCITED TORROIDAL PLASMA SOURCE WITH MAGNETIC CONTROL OF ION DISTRIBUTION and assigned to the present assignee.

25

BACKGROUND OF THE INVENTION
        The present invention is related to semiconductor microelectronic circuit fabrication, and particularly to ion
30   implantation using plasma immersion.

        The formation of semiconductor junctions on the surface of a semiconductor crystal (such as silicon wafer) is generally carried out by implantation of ions of either acceptor or donor impurity species (e.g., Boron or Arsenic)
35   into the surface. Currently, ion implantation is efficiently carried out by ion beam accelerators. An ion beam accelerator raster-scans a beam of donor or acceptor ions across the semiconductor wafer surface. The implanted
40   semiconductor wafer surface is then annealed at elevated temperatures in excess of 600 °C in order to cause the

implanted species to be substituted for silicon atoms within the crystal lattice. This process is defined as dopant activation. The depth of the implanted species below the surface, in conjunction with a subsequent anneal process,

5   determines the junction depth, which is determined by the kinetic energy of the ion beam and subsequent annealing thermal budget. The conductance of the implanted region of the semiconductor is determined by the junction depth and the volume concentration of the thermally activated

10   implanted dopant species. The implanted dopant species concentration is controlled by the rate at which the ion beam is scanned across the semiconductor surface and the beam current. The activated implanted dopant species concentration is controlled by the above, and the subsequent

15   anneal process (temperature and time characteristics). For current semiconductor fabrication processes, in which semiconductor circuit feature size is about 130 nm, ion beam accelerators are suitable for ion implantation because the junction depth is fairly deep (over 330 Angstroms) and the

20   required dopant dose is fairly modest (about 2 X 10^{14} to about 2 X 10^{15} ions/cm^2). Such a modest dopant concentration is fulfilled by an ion beam accelerator with an implant operation lasting only minutes. Because of the deep junction depth, the abruptness of the junction need be no

25   smaller than 6 nm/dec (i.e., nanometers per decade of concentration). Therefore, ion energy distribution is not critical, and some ions may have a kinetic energy that carries them somewhat beyond the desired junction depth without degrading the abruptness beyond the 4.1 nm/dec

30   level. Therefore, techniques for enhancing the ion beam flux that compromise ion energy distribution can be used. These techniques include using an ion beam that has a few times the kinetic energy corresponding to the desired junction depth, or about 2 keV, (and therefore several times

35   the ion flux density), and then electrically decelerating the ion beam down to the correct kinetic energy (e.g., 500

2

eV) just before it impacts the semiconductor wafer surface. The deceleration process is not precise and leaves a fraction of implanted particles (neutrals) above the correct energy level, which is sometimes referred to as a high

5   energy tail or energy contamination. The high energy tail arises from the natural occurrence of neutrals in the ion beam and the immunity of such neutrals from the electrostatic deceleration process. Such neutrals therefore impact the wafer at the original energy (e.g., 2 keV), so

10   that they are implanted below the desired junction depth, due to the high energy tail, causing a loss of junction abruptness. But this is not harmful because of the relatively relaxed requirement for junction abruptness (6 nm/dec). Moreover, rapid thermal annealing by halogen

15   lamps, for example, tends to "wash out" the effect of the high energy tail due to diffusion.

However, as semiconductor circuit feature size decreases with progress in device speed, ion beam

20   accelerators become less efficient. For example, at a feature size of 65 nm, the junction depth is only about 170 Angstroms and the abruptness is much steeper, at 2.8 nm/dec. With such a shallow junction, the required dopant dose is greater (to avoid an increased resistance), or about 10^{15} to

25   about 2 X 10^{16} ions/cm^2. In order to activate such higher dopant concentrations in the silicon crystal, and in order to avoid increasing junction depth during annealing, dynamic surface annealing is advantageously employed, in which the wafer surface (e.g., down to depth of order 1000 Angstroms)

30   is laser-heated to near melting (e.g., 1300 deg. C) for a period of a nanosecond to tens of milliseconds. Dynamic surface annealing activates a higher concentration of dopant and increases junction depth by less than 20 Å compared with rapid thermal annealing. (By comparison, rapid thermal

35   annealing can add over 100 Å to the junction depth, which would double the junction depth in some cases.) However,

3

dynamic surface annealing does not reduce the high energy
tail. Therefore, in order to stay within the more stringent
junction abruptness requirement and in order to avoid a high
energy tail, the ion beam accelerator must be operated in
5   drift mode, in which the ions are accelerated up to but not
beyond the kinetic energy corresponding to the desired
junction depth (e.g., only 500 eV), so that no ions will be
implanted below the desired depth, and no deceleration
process is required. For example, a junction depth of 10-20
10   nm may translate to an ion beam energy of only 500 eV.
Unfortunately, the lower ion energy in drift mode limits the
ion beam flux (and current), so that the time required to
reach the desired high dopant concentration can be as long
as a half hour or one hour. This problem arises
15   particularly in shallow junction implant of light species
such as Boron, in which the beam voltage must be reduced to
avoid high velocity Boron ions being implanted below the
desired junction depth. The problem arises basically
because the space charge effects in the ion beam produce
20   repulsive forces between the ions in the beam in a radial
direction, generally, limiting the beam density and
therefore the beam current. Such effects become more
important as the beam energy is reduced (as it must be for
implanting the lighter elements such as Boron), resulting in
25   lower beam currents and longer implant times.   Such long
implant times greatly limit productivity and increase
production costs. For example, in order to avoid a decrease
in wafer through-put, the number of ion beam implant
machines must be increased. In the future, feature sizes
30   will decrease further, down to 45 nm, so that such problems
will worsen in proportion as the technology advances.

These problems pertain particularly to cases in which
the species to be implanted has a low atomic weight (such as
35   Boron), so that the acceleration voltage must be small,
which translates into a small ion beam flux and a long

4

implant time. For higher atomic weight species (such as
Arsenic), the acceleration voltages are much higher and the
ion beam flux is therefore sufficiently high to keep
implantation times down to an acceptable level. One way of
5   permitting an increased beam acceleration voltage for
lighter implant species such as Boron, in order to improve
ion flux and reduce implant time, is to implant molecular
ions consisting of one Boron atom or more and another
volatile species such as Fluorine, Hydrogen, or other
10   species. Examples of such molecular ions are BF_2, $B_{10}H_{14}$.
Thus, implanting BF_2 permits the use of a much higher beam
energy and therefore a higher and more acceptable ion beam
flux. However, while much of the implanted fluorine tends
to diffuse out of the silicon crystal during annealing, a
15   significant amount does not, leaving some crystal lattice
sites that contain neither a semiconductor atom (Si) nor a
dopant impurity atom (B), thus (for some applications)
reducing the overall quality of the semiconductor material.
Therefore, this technique is not desirable universally for
20   all applications.

In summary, advances in technology dictate a more
shallow junction depth, a greater junction abruptness and a
higher dopant concentration in the semiconductor surface.
25   Such advances in technology (where features size decreases
to 65 nm and ultimately to 45 nm) render ion beam
implantation of lighter dopants such as Boron impractical.
This is because the traditional ion beam implanter provides
too little ion beam flux in such applications.
30
In order to find an ion source having much higher ion
flux for low atomic weight species such as Boron, the field
has turned to an ion source whose flux at a given implant
depth is less affected by the space charge effect or
35   (indirectly) atomic weight, namely a plasma ion source.
Specifically, the semiconductor wafer is immersed in a

plasma consisting of dopant ions (such as Boron ions). However, such plasma ion immersion implantation has been plagued by various difficulties.

One type of plasma immersion ion implantation reactor employs a pulsed D.C. voltage applied to a pedestal supporting the semiconductor wafer in a vacuum chamber filled with a dopant-containing gas such as BF3. The D.C. voltage creates a plasma discharge in the chamber in which Boron ions and other ions dissociated from the BF3 ions are accelerated into the wafer surface. The D.C. voltage maintains the plasma by creation of secondary electrons from collisions with the chamber surfaces or wafer surface. The rate at which such collisions produce secondary electrons depends upon the condition of the chamber surfaces. Accordingly, such a reactor is unacceptably sensitive to changes in the condition of the chamber surfaces due, for example, to contamination of the chamber surfaces. As a result, such a plasma ion immersion implantation reactor cannot maintain a target junction depth or abruptness, for example, and is plagued by contamination problems.

This type of reactor tends to produce a relatively low density plasma and must be operated at relatively high chamber pressure in order to maintain the plasma density. The high chamber pressure and the lower plasma density dictate a thicker plasma sheath with more collisions in the sheath that spread out ion energy distribution. This spreading can result in a larger lateral junction distribution and may reduce junction abruptness. Furthermore, the reactor is sensitive to conditions on the wafer backside because the plasma discharge depends upon ohmic contact between the wafer backside and the wafer support pedestal.

One problem inherent with D.C. voltage applied to the

6

wafer support is that its pulse width must be such that the
dopant ions (e.g., Boron) are accelerated across the plasma
sheath near the wafer surface with sufficient energy to
reach the desired junction depth below the surface, while
5   the pulse width must be limited to avoid (discharge) any
charge build-up on the wafer surface that would cause device
damage (charging damage). The limited pulse width is
problematic in that the periodic decrease in ion energy can
result in deposition on the semiconductor surface rather
10   than implantation, the deposition accumulating in a new
layer that can block implantation during the pulse on times.
Another problem arises because ions must impact the wafer
surface with at least a certain target energy in order to
penetrate the surface up to a desirable depth (the as-
15   implanted junction depth) and become substitutional below
the surface and up to the desired annealed junction depth
during the annealing process. Below this energy, they do
not penetrate the surface up to the as-implanted junction
depth and do not become substitutional at the desired
20   junction depth upon annealing. Moreover, the ions below the
target energy may simply be deposited on the wafer surface,
rather than being implanted, to produce a film that can
impede implantation. Unfortunately, due to resistive and
capacitive charging effects (RC time constant) on dielectric
25   films on the wafer that tend to accompany a D.C. discharge,
the ions reach the target energy during only a fraction of
each pulse period (e.g., during the first microsecond), so
that there is an inherent inefficiency. Moreover, the
resulting spread in ion energy reduces the abruptness of the
30   P-N junction. This problem cannot be solved by simply
increasing the bias voltage, since this would increase the
junction depth beyond the desired junction depth.

Another type of plasma immersion ion implantation
35   reactor employs inductive coupling to generate the plasma,
in addition to the pulsed D.C. voltage on the wafer. This

7

type of reactor reduces the problems associated with plasma maintenance from secondary electrons, but still suffers from the problems associated with pulsed D.C. voltages on the wafer discussed immediately above.

5

Another type of plasma ion immersion implantation reactor employs an RF voltage applied to the wafer support pedestal that both controls ion energy and maintains the plasma. As in the pulsed D.C. voltage discussed above, the

10 RF voltage on the wafer support creates a plasma discharge in the chamber in which Boron ions and other ions dissociated from the BF_3 ions are accelerated into the wafer surface. The RF voltage generates and maintains the plasma mainly by capacitively coupling RF energy from the electrode

15 across the sheath to electrons in the plasma just above the sheath (low pressure case) or electrons in the bulk plasma volume (high pressure case). While such a reactor has reduced sensitivity to chamber surface conditions as compared to reactors employing a pulsed DC bias, it is still

20 quite sensitive. Also, ion energy and flux cannot be independently selected with a single RF power source. Ion flux may still be unacceptably low for high throughput applications with a single RF power source. Contamination due to wall sputtering or etching may also be high due to

25 elevated plasma potential.

Another type of plasma ion immersion implantation reactor employs a microwave power applicator for generating the plasma. This reactor has a microwave waveguide pointed

30 axially downward to a magnetic field centered about the axis. Electron cyclotron resonance (ECR) occurs in a particular surface of the field to produce the plasma (for a microwave frequency of 2.45 GHz, this surface is where the magnetic field is about 875 gauss). The magnetic field is

35 divergent, with a field gradient creating a drift current towards the substrate being processed. This drift current

8

consists of both electrons (directly acted on by the
interaction of microwave induced electric field and
divergent DC magnetic field) and positively-charged ions
(indirectly acted on by the deficit in negative charge

5   formed due to the out-flux of electrons) and corresponding
to a voltage of 10 to 100 eV. One problem is that the
magnetic field gradient is non-uniform, so that the radial .
distribution of plasma ion energy is non-uniform, causing
non-uniform junction depths across the wafer. Another

10   problem is the relatively high ion energy directed at the
wafer, limiting the degree to which junction depths can be
minimized. One way of addressing the non-uniformity issue
is to place the microwave ECR source far above the wafer.
The problem with such an approach is that the ion density

15   and flux is at least proportionately decreased, thus
reducing the productivity of the reactor. A related problem
is that, because the plasma ion density at the wafer surface
is reduced by the increased source-to-wafer distance, the
chamber pressure must be reduced in order to reduce

20   recombination losses. This rules out some applications that
would be advantageously carried out at high pressure
(applications which benefit from wide angular ion energy
distribution) such as conformal doping of polysilicon lines
and three dimensional devices. Another way of addressing the

25   non-uniformity issue is to place another magnet array
between the source and the wafer, in an effort to straighten
the magnetic field. However, the additional magnetic field
would increase magnetic flux at the wafer surface,
increasing the risk of charge damage to semiconductor

30   structures on the wafer.

In summary, plasma immersion ion implantation reactors
have various limitations, depending upon the type of
reactor: plasma reactors in which a pulsed D.C. voltage is

35   applied to the wafer pedestal are too sensitive to chamber
conditions and are inefficient; and plasma reactors with

9

microwave ECR sources tend to produce non-uniform results.
Thus, there is a need for a plasma immersion ion
implantation reactor that is free of the foregoing
limitations.

5

SUMMARY OF THE INVENTION

A plasma immersion ion implantation reactor for
implanting a species into a workpiece includes an enclosure
10 having a side wall and a ceiling defining a chamber, and a
workpiece support pedestal within the chamber for supporting
a workpiece having a surface layer into which the species
are to be ion implanted, the workpiece support pedestal
facing an interior surface of the ceiling so as to define
15 therebetween a process region extending generally across the
diameter of the wafer support pedestal. The reactor further
comprises a source power applicator and an RF plasma source
generator coupled to the source power applicator for
inductively coupling RF source power into the chamber. A
20 gas distribution apparatus furnishes process gas into the
chamber, and a supply of process gas furnishes to the gas
distribution apparatus a process gas containing the species.
An RF bias generator is connected to the workpiece support
pedestal and has an RF bias frequency for establishing an RF
25 bias.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a first case that maintains an
30 overhead torroidal plasma current path.

FIG. 2 is a side view of a case corresponding to the
case of FIG. 1.

35 FIG. 3 is a graph illustrating the behavior of free
fluorine concentration in the plasma with variations in

wafer-to-ceiling gap distance.

FIG. 4 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in RF bias power applied to the workpiece.

FIG. 5 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in RF source power applied to the coil antenna.

FIG. 6 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in reactor chamber pressure.

FIG. 7 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in partial pressure of an inert diluent gas such as Argon.

FIG. 8 is a graph illustrating the degree of dissociation of process gas as a function of source power for an inductively coupled reactor and for a reactor according to an embodiment of the present invention.

FIG. 9 illustrates a variation of the case of FIG. 1.

FIGS. 10 and 11 illustrate a variation of the case of FIG. 1 in which a closed magnetic core is employed.

FIG. 12 illustrates another case of the invention in which a torroidal plasma current path passes beneath the reactor chamber.

FIG. 13 illustrates a variation of the case of FIG. 10 in which plasma source power is applied to a coil wound around a distal portion the closed magnetic core.

FIG. 14 illustrates a case that establishes two parallel torroidal plasma currents.

FIG. 15 illustrates a case that establishes a plurality of individually controlled parallel torroidal plasma currents.

FIG. 16 illustrates a variation of the case of FIG. 15 in which the parallel torroidal plasma currents enter and exit the plasma chamber through the vertical side wall rather than the ceiling.

FIG. 17A illustrates a case that maintains a pair of mutually orthogonal torroidal plasma currents across the surface of the workpiece.

FIG. 17B illustrates the use of plural radial vanes in the case of FIG. 17A.

FIGS. 18 and 19 illustrate an case of the invention in which the torroidal plasma current is a broad belt that extends across a wide path suitable for processing large wafers.

FIG. 20 illustrates a variation of the case of FIG. 18 in which an external section of the torroidal plasma current path is constricted.

FIG. 21 illustrates a variation of the case of FIG. 18 employing cylindrical magnetic cores whose axial positions may be adjusted to adjust ion density distribution across the wafer surface.

FIG. 22 illustrates a variation of FIG. 21 in which a pair of windings are wound around a pair of groups of cylindrical magnetic cores.

12

FIG. 23 illustrates a variation of FIG. 22 in which a single common winding is wound around both groups of cores.

FIG. 24 and 25 illustrate an case that maintains a pair of mutually orthogonal torroidal plasma currents which are wide belts suitable for processing large wafers.

FIG. 26 illustrates a variation of the case of FIG. 25 in which magnetic cores are employed to enhance inductive coupling.

FIG. 27 illustrates a modification of the case of FIG. 24 in which the orthogonal plasma belts enter and exit the reactor chamber through the vertical side wall rather than through the horizontal ceiling.

FIG. 28A illustrates an implementation of the case of FIG. 24 which produces a rotating torroidal plasma current.

FIG. 28B illustrates a version of the case of FIG. 28A that includes magnetic cores.

FIG. 29 illustrates a preferred case of the invention in which a continuous circular plenum is provided to enclose the torroidal plasma current.

FIG. 30 is a top sectional view corresponding to FIG. 29.

FIGS. 31A and 31B are front and side sectional views corresponding to FIG. 30.

FIG. 32 illustrates a variation of the case 29 employing three independently driven RF coils underneath the continuous plenum facing at 120-degree intervals.

13

FIG. 33 illustrates a variation of the case of FIG. 32 in which the three RF coils are driven at 120-degree phase to provide an azimuthally rotating plasma.

FIG. 34 illustrates a variation of the case of FIG. 33 in which RF drive coils are wound around vertical external ends of respective magnetic cores whose opposite ends extend horizontally under the plenum at symmetrically distributed angles.

FIG. 35 is a version of the case of FIG. 17 in which the mutually transverse hollow conduits are narrowed as in the case of FIG. 20.

FIG. 36 is a version of the case of FIG. 24 but employing a pair of magnetic cores 3610, 3620 with respective windings 3630, 3640 therearound for connection to respective RF power sources.

FIG. 37 is a case corresponding to that of FIG. 35 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber.

FIG. 38 is a case corresponding to that of FIG. 38 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber.

FIG. 39 is a case corresponding to that of FIG. 35 in which the external conduits join together in a common plenum 3910.

FIG. 40 is a case corresponding to that of FIG. 36 in which the external conduits join together in a common plenum 4010.

14

FIG. 41 is a case corresponding to that of FIG. 37 in which the external conduits join together in a common plenum 4110.

FIG. 42 is a case corresponding to that of FIG. 38 in which the external conduits join together in a common plenum 4210.

FIG. 43 is a case corresponding to that of FIG. 17 in which the external conduits join together in a common plenum 4310.

FIG. 44 illustrates cases a reactor similar to that of FIG. 1 and having a magnetic pole piece for controlling plasma ion density uniformity.

FIG. 45 illustrates a reactor like that of FIG. 44 in which the magnetic pole piece has a reduced diameter near the ceiling surface, and the ceiling is a dual zone gas distribution plate.

FIGS. 46, 47 and 48 illustrate different shapes for the pole piece.

FIG. 49 illustrates one implementation of the gas distribution plate.

FIG. 50 is a detailed view of a gas injection orifice in FIG. 49.

FIG. 51 is a graph depicting the magnetic field that the magnetic pole piece can generate.

FIG. 52 is a graph of the magnetic field magnitude as a function of radius.

FIGS. 53 and 54 illustrate different ways of controlling process gas flow.

FIGS. 55A and 55B illustrate the use of a splitter in the torroidal plasma path.

FIGS. 56A, 56B and 56C illustrate use of splitters where the torroidal plasma current enters the chamber vertically.

FIGS. 57 and 58 illustrate different shapes for a splitter.

FIGS. 59A and 59B illustrate use of splitters where the torroidal plasma current enters the chamber radially.

FIGS. 60, 61, 62 and 63 illustrate the use of splitters where the torroidal plasma current is introduced vertically at a corner of the chamber.

FIG. 64 illustrates how a splitter may extend only part of the process region height.

FIGS. 65A, 65B and 66 illustrate a splitter design adapted to increase the effective radial path length of the torroidal plasma current inside the chamber for a given chamber diameter.

FIG. 67 illustrates the use of MERIE magnets with the torroidal plasma current source of FIG. 1.

FIGS. 68 and 69 illustrate the use of fins to better confine the torroidal plasma current to the processing region.

FIGS. 70, 71 and 72 illustrate an RF power applicator

having distributed inductances.

FIG. 72 illustrates distributed inductances corresponding to the FIGS. 70, 71A and 71B.

FIG. 73 illustrates a circular arrangement of the distributed inductances of FIG. 72.

FIG. 74 illustrates distributed inductances and capacitances in an arrangement corresponding to that of FIGS. 71A and 71B.

FIGS. 75 and 76 are schematic diagrams illustrating different ways of inductively coupling RF power using the magnetic core of FIGS. 71A and 71B.

FIG. 77 illustrates the use of an insulator layer to electrically isolate the termination sections and torroidal tubes of FIG. 44.

FIG. 78 illustrates how the uniformity control magnet or magnetic pole may be placed under the wafer support pedestal.

FIG. 79 depicts an inductively coupled plasma immersion ion implantation reactor having an RF bias power applicator.

FIGS. 80A, 80B and 80C illustrate, respectively, an applied pulsed D.C. bias voltage, the corresponding sheath voltage behavior and an applied RF bias voltage.

FIGS. 81A, 81B, 81C and 81D illustrate, respectively, an energy distribution of ion flux, a cycle of applied RF bias voltage, ion saturation current as a function of D.C. bias voltage, and energy distribution of ion flux for different frequencies of RF bias voltage.

17

FIGS. 82A and 82B illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in a push-pull mode.

FIGS. 82C and 82D illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in an in-synchronism mode.

FIGS. 82E and 82F illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in a symmetric mode.

FIGS. 82G and 82H illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in a non-symmetric mode.

FIGS. 83A and 83B illustrate different versions of a capacitively coupled plasma immersion ion implantation reactor having an RF bias power applicator.

FIG. 84 illustrates a plasma immersion ion implantation reactor having a reentrant torroidal path plasma source.

FIG. 85 illustrates a plasma immersion ion implantation reactor having a torroidal plasma source with two intersecting reentrant plasma paths.

FIG. 86 illustrates an interior surface of the ceiling of the reactor of FIG. 85.

FIG. 87 illustrates a gas distribution panel of the reactor of FIG. 85.

18

FIG. 88 is a partial view of the reactor of FIG. 85 modified to include a plasma control center electromagnet.

FIGS. 89A and 89B are side and top views, respectively, of a version of the reactor of FIG. 88 having, in addition, a plasma control outer electromagnet.

FIGS. 90A, 90B and 90C are cross-sectional side view of the outer electromagnet of FIG. 89A with different gap distances of a bottom plate for regulating magnetic flux.

FIG. 91 illustrates an RF bias power coupling circuit in the reactor of FIG. 85.

FIG. 92 depicts an RF bias voltage waveform in accordance with a bias voltage control feature.

FIG. 93 is a block diagram illustrating a control system for controlling bias voltage in accordance with the feature illustrated in FIG. 92.

FIG. 94 is a top view of a vacuum control valve employed in the reactor of FIG. 85.

FIG. 95 is a cross-sectional side view of the valve of FIG. 94 in the closed position.

FIG. 96 is a side view of the interior surface of the housing of the valve of FIG. 95 with an orientation at right angles to that of FIG. 95.

FIG. 97 is a cross-sectional side view of a high voltage wafer support pedestal useful in the reactor of FIG. 85.

FIG. 98 is an enlarged cross-sectional view of the

19

wafer support pedestal of FIG. 97 illustrating a fastener therein.

FIG. 99 is a block diagram illustrating an ion implantation processing system including a plasma immersion ion implantation reactor.

FIG. 100 is a graph illustrating electron density as a function of applied plasma source power for the inductively coupled plasma immersion ion implantation reactor of FIG. 79 and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 101 is a graph illustrating free fluorine density as a function of applied plasma source power for the inductively coupled plasma immersion ion implantation reactor of FIG. 79 and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 102 is a graph illustrating electron density as a function of applied plasma source power for the capacitively coupled plasma immersion ion implantation reactor of FIG. 83A and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 103 is a graph illustrating dopant concentration as a function of junction depth for different ion energies in the reactor of FIG. 85 and in a convention ion beam implant machine.

FIG. 104 is a graph illustrating dopant concentration before and after post-implant rapid thermal annealing.

FIG. 105 is a graph illustrating dopant concentration before and after dynamic surface annealing in the torroidal source plasma immersion ion implantation reactor of FIG. 85

and in a convention ion beam implant machine.

FIG. 106 is a graph depicting wafer resistivity after ion implantation and annealing as a function of junction depth obtained with the reactor of FIG. 85 using dynamic surface annealing and with a conventional ion beam implant machine using rapid thermal annealing.

FIG. 107 is a graph depicting implanted dopant concentration obtained with the reactor of FIG. 85 before and after dynamic surface annealing.

FIG. 108 is a graph of RF bias voltage in the reactor of FIG. 85 (left ordinate) and of beamline voltage in a beamline implant machine (right ordinate) as a function of junction depth.

FIG. 109 is a cross-sectional view of the surface of a wafer during ion implantation of source and drain contacts and of the polysilicon gate of a transistor.

FIG. 110 is a cross-sectional view of the surface of a wafer during ion implantation of the source and drain extensions of a transistor.

FIG. 111 is a flow diagram illustrating an ion implantation process carried out using the reactor of FIG. 85.

FIG. 112 is a flow diagram illustrating a sequence of possible pre-implant, ion implant and possible post implant processes carried using the reactor of FIG. 85 in the system of FIG. 99.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

21

Description of a Torroidal Source Reactor:

Referring to FIG. 1, a plasma reactor chamber 100 enclosed by a cylindrical side wall 105 and a ceiling 110 houses a wafer pedestal 115 for supporting a semiconductor wafer or workpiece 120. A process gas supply 125 furnishes process gas into the chamber 100 through gas inlet nozzles 130a-130d extending through the side wall 105. A vacuum pump 135 controls the pressure within the chamber 100, typically holding the pressure below 0.5 milliTorr (mT). A half-torroidal hollow tube enclosure or conduit 150 extends above the ceiling 110 in a half circle. The conduit 150, although extending externally outwardly from ceiling 110, is nevertheless part of the reactor and forms a wall of the chamber. Internally it shares the same evacuated atmosphere as exists elsewhere in the reactor. In fact, the vacuum pump 135, instead of being coupled to the bottom of the main part of the chamber as illustrated in FIG. 1, may instead be coupled to the conduit 150. The conduit 150 has one open end 150a sealed around a first opening 155 in the reactor ceiling 110 and its other end 150b sealed around a second opening 160 in the reactor ceiling 110. The two openings or ports 150, 160 are located on generally opposite sides of the wafer support pedestal 115. The hollow conduit 150 is reentrant in that it provides a flow path which exits the main portion of the chamber at one opening and re-enters at the other opening. In this specification, the conduit 150 may be described as being half-torroidal, in that the conduit is hollow and provides a portion of a closed path in which plasma may flow, the entire path being completed by flowing across the entire process region overlying the wafer support pedestal 115. Notwithstanding the use of the term **torroidal,** the trajectory of the path as well as the cross-sectional shape of the path or conduit 150 may be circular or non-circular, and may be square, rectangular or any other shape either a regular shape or irregular.

22

The external conduit 150 may be formed of a relatively thin conductor such as sheet metal, but sufficiently strong to withstand the vacuum within the chamber. In order to suppress eddy currents in the sheet metal of the hollow conduit 150 (and thereby facilitate coupling of an RF inductive field into the interior of the conduit 150), an insulating gap 152 extends across and through the hollow conduit 150 so as to separate it into two tubular sections. The gap 152 is filled by a ring 154 of insulating material such as a ceramic in lieu of the sheet metal skin, so that the gap is vacuum tight. A second insulating gap 153 may be provided, so that one section of the conduit 150 is electrically floating. A bias RF generator 162 applies RF bias power to the wafer pedestal 115 and wafer 120 through an impedance match element 164.

The hollow conduit 150 may be formed of a machined metal, such as aluminum or aluminum alloy. Passages for liquid cooling or heating may be incorporated in the walls of the hollow conduit.

Alternatively, the hollow conduit 150 may be formed of a non-conductive material instead of the conductive sheet metal. The non-conductive material may be a ceramic, for example. In such an alternative case, neither gap 152 or 153 is required.

An antenna 170 such as a winding or coil 165 disposed on one side of the hollow conduit 150 and wound around an axis parallel to the axis of symmetry of the half-torroidal tube is connected through an impedance match element 175 to an RF power source 180. The antenna 170 may further include a second winding 185 disposed on the opposite side of the hollow conduit 150 and wound in the same direction as the first winding 165 so that the magnetic fields from both

23

windings add constructively.

Process gases from the chamber 100 fill the hollow
conduit 150. In addition, a separate process gas supply 190
5   may supply process gases directly in to the hollow conduit
150 through a gas inlet 195. The RF field in the external
hollow conduit 150 ionizes the gases in the tube to produce
a plasma. The RF field induced by the circular coil antenna
170 is such that the plasma formed in the tube 150 reaches
10   through the region between the wafer 120 and the ceiling 110
to complete a torroidal path that includes the half-
torroidal hollow conduit 150. As employed herein, the term
torroidal refers to the closed and solid nature of the path,
but does not refer or limit its cross-sectional shape or
15   trajectory, either of which may be circular or non-circular
or square or otherwise. Plasma circulates (oscillates)
through the complete torroidal path or region which may be
thought of as a closed plasma circuit. The torroidal region
extends across the diameter of the wafer 120 and, in certain
20   cases, has a sufficient width in the plane of the wafer so
that it overlies the entire wafer surface.

The RF inductive field from the coil antenna 170
includes a magnetic field which itself is closed (as are all
25   magnetic fields), and therefore induces a plasma current
along the closed torroidal path described here. It is
believed that power from the RF inductive field is absorbed
at generally every location along the closed path, so that
plasma ions are generated all along the path. The RF power
30   absorption and rate of plasma ion generation may vary among
different locations along the closed path depending upon a
number of factors. However, the current is generally
uniform along the closed path length, although the current
density may vary. This current alternates at the frequency
35   of the RF signal applied to the antenna 170. However, since

24

the current induced by the RF magnetic field is closed, the
current must be conserved around the circuit of the closed
path, so that the amount of current flowing in any portion
of the closed path is generally the same as in any other
5   portion of the path. As will be described below, this fact
is exploited in the invention to great advantage.

The closed torroidal path through which the plasma
current flows is bounded by plasma sheaths formed at the
10   various conductive surfaces bounding the path. These
conductive surfaces include the sheet metal of the hollow
conduit 150, the wafer (and/or the wafer support pedestal)
and the ceiling overlying the wafer. The plasma sheaths
formed on these conductive surfaces are charge-depleted
15   regions produced as the result of the charge imbalance due
to the greater mobility of the low-mass negative electrons
and the lesser mobility of the heavy-mass positive ions.
Such a plasma sheath has an electric field perpendicular to
the local surface underlying the sheath. Thus, the RF
20   plasma current that passes through the process region
overlying the wafer is constricted by and passes between the
two electric fields perpendicular to the surface of the
ceiling facing the wafer and the surface of the wafer facing
the gas distribution plate. The thickness of the sheath
25   (with RF bias applied to the workpiece or other electrode)
is greater where the electric field is concentrated over a
small area, such as the wafer, and is less in other
locations such as the sheath covering the ceiling and the
large adjoining chamber wall surfaces. Thus, the plasma
30   sheath overlying the wafer is much thicker. The electric
fields of the wafer and ceiling/gas distribution plate
sheaths are generally parallel to each other and
perpendicular to the direction of the RF plasma current flow
in the process region.
35

When RF power is first applied to the coil antenna 170,

a discharge occurs across the gap 152 to ignite a
capacitively coupled plasma from gases within the hollow
conduit 150. Above a threshold power level, the discharge
and plasma current become spatially continuous through the
5   length of the hollow conduit 150 and along the entire
torroidal path. Thereafter, as the plasma current through
the hollow conduit 150 increases, the inductive coupling of
the RF field becomes more dominant so that the plasma
becomes an inductively coupled plasma. Alternatively,
10   plasma may be initiated by other means, such as by RF bias
applied to the workpiece support or other electrode or by a
spark or ultraviolet light source.

In order to avoid edge effects at the wafer periphery,
15   the ports 150, 160 are separated by a distance that exceeds
the diameter of the wafer. For example, for a 12 inch
diameter wafer, the ports 150, 160 are about 14 to 22 inches
apart. For an 8 inch diameter wafer, the ports 150, 160 are
about 9 to 16 inches apart.
20

Notwithstanding the use of the term "wafer", the
workpiece may be any shape, such as rectangular. The
workpiece material may be a semiconductor, insulator, or
conductor, or a combination of various materials. The
25   workpiece may have 2-dimensional or 3-dimensional structure,
as well.

Advantages:
30   A significant advantage is that power from the RF
inductive field is absorbed throughout the relatively long
closed torroidal path (i.e., long relative to the gap length
between the wafer and the reactor ceiling), so that RF power
absorption is distributed over a large area. As a result,
35   the RF power density in the vicinity of the wafer-to-ceiling
gap (i.e., the process region 121 best shown in FIG. 2, not

26

to be confused with the insulating gap 152) is relatively
low, thus reducing the likelihood of device damage from RF
fields. In contrast, in prior inductively coupled reactors,
all of the RF power is absorbed within the narrow wafer-to-
5   ceiling gap, so that it is greatly concentrated in that
region. Moreover, this fact often limits the ability to
narrow the wafer-to-ceiling gap (in the quest of other
advantages) or, alternatively, requires greater
concentration of RF power in the region of the wafer. Thus,
10   the invention overcomes a limitation of long standing in the
art. This aspect enhances process performance for some
applications by reducing residency time of the reactive
gases through a dramatic reduction in volume of the process
region or process zone overlying the wafer, as discussed
15   previously herein.

A related and even more important advantage is that the
plasma density at the wafer surface can be dramatically
increased without increasing the RF power applied to the
20   coil antenna 170 (leading to greater efficiency). This is
accomplished by reducing the cross-sectional area of the
torroidal path in the vicinity of the pedestal surface and
wafer 120 relative to the remainder of the torroidal path.
By so constricting the torroidal path of the plasma current
25   near the wafer only, the density of the plasma near the
wafer surface is increased proportionately. This is because
the torroidal path plasma current through the hollow conduit
150 must be at least nearly the same as the plasma current
through the pedestal-to-ceiling (wafer-to-ceiling) gap.

30

A significant difference over the prior art is that not
only is the RF field remote from the workpiece, and not only
can ion density be increased at the wafer surface without
increasing the applied RF field, but the plasma ion density
35   and/or the applied RF field may be increased without
increasing the minimum wafer-to-ceiling gap length.

27

Formerly, such an increase in plasma density necessitated an increase in the wafer-to-ceiling gap to avoid strong fields at the wafer surface. In contrast, in the present invention the enhanced plasma density is realized without requiring

5   any increase in the wafer-to-ceiling gap to avoid a concomitant increase in RF magnetic fields at the wafer surface. This is because the RF field is applied remotely from the wafer and moreover need not be increased to realize an increase in plasma density at the wafer surface. As a

10   result, the wafer-to-ceiling gap can be reduced down to a fundamental limit to achieve numerous advantages. For example, if the ceiling surface above the wafer is conductive, then reducing the wafer-to-ceiling gap improves the electrical or ground reference provided by the

15   conductive ceiling surface. A fundamental limit on the minimum wafer-to-ceiling gap length is the sum of the thicknesses of the plasma sheaths on the wafer surface and on the ceiling surface.

20   A further advantage of the invention is that because the RF inductive field is applied along the entire torroidal path of the RF plasma current (so that its absorption is distributed as discussed above), the chamber ceiling 110, unlike with most other inductively powered reactors, need

25   not function as a window to an inductive field and therefore may be formed of any desired material, such as a highly conductive and thick metal, and therefore may comprise a conductive gas distribution plate as will be described below, for example. As a result, the ceiling 110 readily

30   provides a reliable electric potential or ground reference across the entire plane of the pedestal or wafer 120.

35   <u>Increasing the Plasma Ion Density:</u>
         One way of realizing higher plasma density near the

wafer surface by reducing plasma path cross-sectional area over the wafer is to reduce the wafer-to-ceiling gap length. This may be accomplished by simply reducing the ceiling height or by introducing a conductive gas distribution plate or showerhead over the wafer, as illustrated in FIG. 2. The gas distribution showerhead 210 of FIG. 2 consists of a gas distribution plenum 220 connected to the gas supply 125 and communicating with the process region over the wafer 120 through plural gas nozzle openings 230. The advantage of the conductive showerhead 210 is two-fold: First, by virtue of its close location to the wafer, it constricts the plasma path over the wafer surface and thereby increases the density of the plasma current in that vicinity. Second, it provides a uniform electrical potential reference or ground plane close to and across the entire wafer surface.

In order to avoid arcing across the openings 230, each opening 230 may be relatively small, on the order of a millimeter (e.g., hole diameter is approximately 0.5 mm). The spacing between adjacent openings may be on the order of a several millimeters.

The conductive showerhead 210 constricts the plasma current path rather than providing a short circuit through itself because a plasma sheath is formed around the portion of the showerhead surface immersed in the plasma. The sheath has a greater impedance to the plasma current than the space between the wafer 120 and the showerhead 210, and therefore virtually all the plasma current goes around the conductive showerhead 210.

It is not necessary to employ a showerhead (e.g., the showerhead 210) in order to constrict the torroidal plasma current or path in the vicinity of the process region overlying the wafer. The path constriction and consequent increase in plasma ion density in the process region may be

29

achieved without the showerhead 210 by similarly reducing the wafer-to-ceiling height. If the showerhead 210 is eliminated in this manner, then the process gases may be supplied into the chamber interior by means of conventional

5   gas inlet nozzles, gas diffusers, or gas slots (not shown).

One advantage of the showerhead 210 is that different mixtures of reactive and inert process gas ratios may be introduced through different orifices 230 at different

10   radii, in order to finely adjust the uniformity of plasma effects on photoresist, for example. Thus, for example, a greater proportion of inert gas to reactive gas may be supplied to the orifices 230 lying outside a median radius while a greater proportion of reactive gas to inert gas may

15   be supplied to the orifices 230 within that median radius.

As will be described below, another way in which the torroidal plasma current path may be constricted in the process region overlying the wafer (in order to increase

20   plasma ion density over the wafer) is to increase the plasma sheath thickness on the wafer by increasing the RF bias power applied to the wafer support pedestal. Since as described previously the plasma current across the process region is confined between the plasma sheath at the wafer

25   surface and the plasma sheath at the ceiling (or showerhead) surface, increasing the plasma sheath thickness at the wafer surface necessarily decreases the cross-section of the portion of the torroidal plasma current within process region, thereby increasing the plasma ion density in the

30   process region. Thus, as will be described more fully later in this specification, as RF bias power on the wafer support pedestal is increased, plasma ion density near the wafer surface is increased accordingly.

35

High Etch Selectivity at High Etch Rates:

30

The invention solves the problem of poor etch selectivity which sometimes occurs with a high density plasma. The reactor of FIGS. 1 and 2 has a silicon dioxide-to-photoresist etch selectivity as high as that of a

5 capacitively coupled plasma reactor (about 7:1) while providing high etch rates approaching that of a high density inductively coupled plasma reactor. It is believed that the reason for this success is that the reactor structure of FIGS. 1 and 2 reduces the degree of dissociation of the

10 reactive process gas, typically a fluorocarbon gas, so as to reduce the incidence of free fluorine in the plasma region over the wafer 120. Thus, the proportion of free fluorine in the plasma relative to other species dissociated from the fluorocarbon gas is desirably reduced. Such other species

15 include the protective carbon-rich polymer precursor species formed in the plasma from the fluorocarbon process gas and deposited on the photoresist as a protective polymer coating. They further include less reactive etchant species such as CF and CF_2 formed in the plasma from the

20 fluorocarbon process gas. Free fluorine tends to attack photoresist and the protective polymer coating formed thereover as vigorously as it attacks silicon dioxide, thus reducing oxide-to-photoresist etch selectivity. On the other hand, the less reactive etch species such as CF_2 or CF

25 tend to attack photoresist and the protective polymer coating formed thereover more slowly and therefore provide superior etch selectivity.

It is believed that the reduction in the dissociation

30 of the plasma species to free fluorine is accomplished in the invention by reducing the residency time of the reactive gas in the plasma. This is because the more complex species initially dissociated in the plasma from the fluorocarbon process gas, such as CF_2 and CF are themselves ultimately

35 dissociated into simpler species including free fluorine, the extent of this final step of dissociation depending upon

31

the residency time of the gas in the plasma. The term "residency time" or "residence time" as employed in this specification corresponds generally to the average time that a process gas molecule and the species dissociated from the

5   that molecule are present in the process region overlying the workpiece or wafer. This time or duration extends from the initial injection of the molecule into the process region until the molecule and/or its dissociated progeny are pass out of the process region along the closed torroidal

10   path described above that extends through the processing zone.

It is also believed that the reduction in the dissociation of the plasma species to free fluorine is

15   accomplished by reducing the power density of the applied plasma source power as compared to conventional inductively coupled plasma sources. As stated above, power from the RF inductive field is absorbed throughout the relatively long closed torroidal path (i.e., long relative to the gap length

20   between the wafer and the reactor ceiling), so that RF power absorption is distributed over a large area. As a result, the RF power density in the vicinity of the wafer-to-ceiling gap (i.e., the process region 121 best shown in FIG. 2, not to be confused with the insulating gap 152) is relatively

25   low, thus reducing the dissociation of molecular gases.

As stated above, the invention enhances etch selectivity by reducing the residency time in the process region of the fluorocarbon process gas. The reduction in

30   residency time is achieved by constricting the plasma volume between the wafer 120 and the ceiling 110.

The reduction in the wafer-to-ceiling gap or volume has certain beneficial effects. First, it increases plasma

35   density over the wafer, enhancing etch rate. Second, residency time falls as the volume is decreased. As

<div align="center">32</div>

referred to above, the small volume is made possible in the present invention because, unlike conventional inductively coupled reactors, the RF source power is not deposited within the confines of the process region overlying the

5   wafer but rather power deposition is distributed along the entire closed torroidal path of the plasma current. Therefore, the wafer-to-ceiling gap can be less than a skin depth of the RF inductive field, and in fact can be so small as to significantly reduce the residency time of the

10   reactive gases introduced into the process region, a significant advantage.

There are two ways of reducing the plasma path cross-section and therefore the volume over the wafer 120. One is

15   to reduce the wafer-to-showerhead gap distance. The other is to increase the plasma sheath thickness over the wafer by increasing the bias RF power applied to the wafer pedestal 115 by the RF bias power generator 162, as briefly mentioned above. Either method results in a reduction in free

20   fluorine content of the plasma in the vicinity of the wafer 120 (and consequent increase in dielectric-to-photoresist etch selectivity) as observed using optical emission spectroscopy (OES) techniques.

25   There are three additional methods of the invention for reducing free fluorine content to improve etch selectivity. One method is to introduce a non-chemically reactive diluent gas such as argon into the plasma. The argon gas may be introduced outside and above the process region by injecting

30   it directly into the hollow conduit 150 from the second process gas supply 190, while the chemically reactive process gases (fluorocarbon gases) enter the chamber only through the showerhead 210. With this advantageous arrangement, the argon ions, neutrals, and excited neutrals

35   propagate within the torroidal path plasma current and through the process region across the wafer surface to

33

dilute the newly introduced reactive (e.g., fluorocarbon) gases and thereby effectively reduce their residency time over the wafer. Another method of reducing plasma free fluorine content is to reduce the chamber pressure. A

5 further method is to reduce the RF source power applied to the coil antenna 170.

FIG. 3 is a graph illustrating a trend observed in the invention in which the free fluorine content of the plasma

10 decreases as the wafer-to-showerhead gap distance is decreased. FIG. 4 is a graph illustrating that the free fluorine content of the plasma is decreased by decreasing the plasma bias power applied to the wafer pedestal 115. FIG. 5 is a graph illustrating that plasma free fluorine

15 content is reduced by reducing the RF source power applied to the coil antenna 170. FIG. 6 is a graph illustrating that the free fluorine content is reduced by reducing chamber pressure. FIG. 7 is a graph illustrating that plasma free fluorine content is reduced by increasing the

20 diluent (Argon gas) flow rate into the tubular enclosure 150. The graphs of FIGS. 3-7 are merely illustrative of plasma behavioral trends inferred from numerous OES observations and do not depict actual data.

25

Wide Process Window:

The chamber pressure is generally less than 0.5 T and can be as low as 1 mT. The process gas may be C_4F_8 injected into the chamber 100 through the gas distribution showerhead

30 at a flow rate of about 15 cc/m with 150 cc/m of Argon, with the chamber pressure being maintained at about 20 mT. Alternatively, the Argon gas flow rate may be increased to 650 cc/m and the chamber pressure to 60 mT. The antenna 170 may be excited with about 500 Watts of RF power at 13 MHz.

35 The wafer-to-showerhead gap may be about 0.3 inches to 2 inches. The bias RF power applied to the wafer pedestal may

34

be 13 MHz at 2000 Watts.   Other selections of frequency may
be made. The source power applied to the coil antenna 170
may be as low as 50 kHz or as high as several times 13 MHz
or higher. The same is true of the bias power applied to
5   the wafer pedestal.

        The process window for the reactor of FIGS. 1 and 2 is
far wider than the process window for a conventional
inductively coupled reactor. This is illustrated in the
10   graph of FIG. 8, showing the specific neutral flux of free
fluorine as a function of RF source power for a conventional
inductive reactor and for the reactor of FIGS. 1 and 2. For
the conventional inductively coupled reactor, FIG. 8 shows
that the free fluorine specific flux begins to rapidly
15   increase as the source power exceeds between 50 and 100
Watts. In contrast, the reactor of FIGS. 1 and 2 can accept
source power levels approaching 1000 Watts before the free
fluorine specific flux begins to increase rapidly.
Therefore, the source power process window in the invention
20   is nearly an order of magnitude wider than that of a
conventional inductively coupled reactor, a significant
advantage.

25   Dual Advantages:
        The constriction of the torroidal plasma current path
in the vicinity of the wafer or workpiece produces two
independent advantages without any significant tradeoffs of
other performance criteria: (1) the plasma density over the
30   wafer is increased without requiring any increase in plasma
source power, and (2) the etch selectivity to photoresist or
other materials is increased, as explained above. It is
believed that in prior plasma reactors it has been
impractical if not impossible to increase the plasma ion
35   density by the same step that increases etch selectivity.
Thus, the dual advantages realized with the torroidal plasma
35

source of the present invention appear to be a revolutionary departure from the prior art.

5   Other Embodiments:

FIG. 9 illustrates a modification of the case of FIG. 1 in which the side antenna 170 is replaced by a smaller antenna 910 that fits inside the empty space between the ceiling 110 and the hollow conduit 150. The antenna 910 is
10   a single coil winding centered with respect to the hollow conduit 150.

FIGS. 10 and 11 illustrate how the case of FIG. 1 may be enhanced by the addition of a closed magnetically
15   permeable core 1015 that extends through the space between the ceiling 110 and the hollow conduit 150. The core 1015 improves the inductive coupling from the antenna 170 to the plasma inside the hollow conduit 150.

20   Impedance match may be achieved without the impedance match circuit 175 by using, instead, a secondary winding 1120 around the core 1015 connected across a tuning capacitor 1130. The capacitance of the tuning capacitor 1130 is selected to resonate the secondary winding 1120 at
25   the frequency of the RF power source 180. For a fixed tuning capacitor 1130, dynamic impedance matching may be provided by frequency tuning and/or by forward power servoing.

30   FIG. 12 illustrates a case of the invention in which a hollow tube enclosure 1250 extends around the bottom of the reactor and communicates with the interior of the chamber through a pair of openings 1260, 1265 in the bottom floor of the chamber. A coil antenna 1270 follows along side the
35   torroidal path provided by the hollow tube enclosure 1250 in the manner of the case of FIG. 1. While FIG. 12 shows the

36

vacuum pump 135 coupled to the bottom of the main chamber, it may just as well be coupled instead to the underlying conduit 1250.

5   FIG. 13 illustrates a variation of the case of FIGS. 10 and 11, in which the antenna 170 is replaced by an inductive winding 1320 surrounding an upper section of the core 1015. Conveniently, the winding 1320 surrounds a section of the core 1015 that is above the conduit 150 (rather than below

10   it). However, the winding 1320 can surround any section of the core 1015.

        FIG. 14 illustrates an extension of the concept of FIG. 13 in which a second hollow tube enclosure 1450 runs

15   parallel to the first hollow conduit 150 and provides a parallel torroidal path for a second torroidal plasma current. The tube enclosure 1450 communicates with the chamber interior at each of its ends through respective openings in the ceiling 110. A magnetic core 1470 extends

20   under both tube enclosures 150, 1450 and through the coil antenna 170.

        FIG. 15 illustrates an extension of the concept of FIG. 14 in which an array of parallel hollow tube enclosures

25   1250a, 1250b, 1250c, 1250d provide plural torroidal plasma current paths through the reactor chamber. In the case of FIG. 15, the plasma ion density is controlled independently in each individual hollow conduit 1250a-d by an individual coil antenna 170a-d, respectively, driven by an independent

30   RF power source 180a-d, respectively. Individual cylindrical open cores 1520a-1520d may be separately inserted within the respective coil antennas 170a-d. In this case, the relative center-to-edge ion density distribution may be adjusted by separately adjusting the

35   power levels of the individual RF power sources 180a-d.

37

FIG. 16 illustrates a modification of the case of FIG. 15 in which the array of tube enclosures 1250a-d extend through the side wall of the reactor rather than through the ceiling 110. Another modification illustrated in FIG. 16 is the use of a single common magnetic core 1470 adjacent all of the tube enclosures 1250a-d and having the antenna 170 wrapped around it so that a single RF source excites the plasma in all of the tube enclosures 1250a-d.

FIG. 17A illustrates a pair of orthogonal tube enclosures 150-1 and 150-2 extending through respective ports in the ceiling 110 and excited by respective coil antennas 170-1 and 170-2. Individual cores 1015-1 and 1015-2 are within the respective coil antennas 170-1 and 170-2. This case creates two mutually orthogonal torroidal plasma current paths over the wafer 120 for enhanced uniformity. The two orthogonal torroidal or closed paths are separate and independently powered as illustrated, but intersect in the process region overlying the wafer, and otherwise do not interact. In order to assure separate control of the plasma source power applied to each one of the orthogonal paths, the frequency of the respective RF generators 180a, 180b of FIG. 17 are different, so that the operation of the impedance match circuits 175a, 175b is decoupled. For example, the RF generator 180a may produce an RF signal at 11 MHz while the RF generator 180b may produce an RF signal at 12 MHz. Alternatively, independent operation may be achieved by offsetting the phases of the two RF generators 180a, 180b.

FIG. 17B illustrates how radial vanes 181 may be employed to guide the torroidal plasma currents of each of the two conduits 150-1, 150-2 through the processing region overlying the wafer support. The radial vanes 181 extend between the openings of each conduit near the sides of the chamber up to the edge of the wafer support. The radial

38

vanes 181 prevent diversion of plasma from one torroidal
path to the other torroidal path, so that the two plasma
currents only intersect within the processing region
overlying the wafer support.

5

Cases Suitable for Large Diameter Wafers:
     In addition to the recent industry trends toward
smaller device sizes and higher device densities, another
10   trend is toward greater wafer diameters. For example, 12-
inch diameter wafers are currently entering production, and
perhaps larger diameter wafers will be in the future. The
advantage is greater throughput because of the large number
of integrated circuit die per wafer. The disadvantage is
15   that in plasma processing it is more difficult to maintain a
uniform plasma across a large diameter wafer. The following
cases of the present invention are particularly adapted for
providing a uniform plasma ion density distribution across
the entire surface of a large diameter wafer, such as a 12-
20   inch diameter wafer.

     FIGS. 18 and 19 illustrate a hollow tube enclosure 1810
which is a wide flattened rectangular version 1850 of the
hollow conduit 150 of FIG. 1 that includes an insulating gap
25   1852. This version produces a wide "belt" of plasma that is
better suited for uniformly covering a large diameter wafer
such as a 12-inch diameter wafer or workpiece. The width W
of the tube enclosure and of the pair of openings 1860, 1862
in the ceiling 110 may exceed the wafer by about 5% or more.
30   For example, if the wafer diameter is 10 inches, then the
width W of the rectangular tube enclosure 1850 and of the
openings 1860, 1862 is about 11 inches. FIG. 20 illustrates
a modified version 1850' of the rectangular tube enclosure
1850 of FIGS. 18 and 19 in which a portion 1864 of the
35   exterior tube enclosure 1850 is constricted.

39

FIG. 20 further illustrates the optional use of focusing magnets 1870 at the transitions between the constricted and unconstricted portions of the enclosure 1850. The focusing magnets 1870 promote a better movement of the plasma between the constricted and unconstricted portions of the enclosure 1850, and specifically promote a more uniform spreading out of the plasma as it moves across the transition between the constricted portion 1864 and the unconstricted portion of the tube enclosure 1850.

FIG. 21 illustrates how plural cylindrical magnetic cores 2110 may be inserted through the exterior region 2120 circumscribed by the tube enclosure 1850. The cylindrical cores 2110 are generally parallel to the axis of symmetry of the tube enclosure 1850. FIG. 22 illustrates a modification of the case of FIG. 21 in which the cores 2110 extend completely through the exterior region 2120 surrounded by the tube enclosure 1850 are replaced by pairs of shortened cores 2210, 2220 in respective halves of the exterior region 2120. The side coils 165, 185 are replaced by a pair of coil windings 2230, 2240 surrounding the respective core pairs 2210, 2220. In this case, the displacement D between the core pairs 2210, 2220 may be changed to adjust the ion density near the wafer center relative to the ion density at the wafer circumference. A wider displacement D reduces the inductive coupling near the wafer center and therefore reduces the plasma ion density at the wafer center. Thus, an additional control element is provided for precisely adjusting ion density spatial distribution across the wafer surface. FIG. 23 illustrates a variation of the case of FIG. 22 in which the separate windings 2230, 2240 are replaced by a single center winding 2310 centered with respect to the core pairs 2210, 2220.

FIGS. 24 and 25 illustrate a case providing even greater uniformity of plasma ion density distribution across

40

the wafer surface. In the case of FIGS. 24 and 25, two
torroidal plasma current paths are established that are
transverse to one another and are mutually orthogonal. This
is accomplished by providing a second wide rectangular
5   hollow enclosure 2420 extending transversely and
orthogonally relative to the first tube enclosure 1850. The
second tube enclosure 2420 communicates with the chamber
interior through a pair of openings 2430, 2440 through the
ceiling 110 and includes an insulating gap 2452. A pair of
10   side coil windings 2450, 2460 along the sides of the second
tube enclosure 2420 maintain a plasma therein and are driven
by a second RF power supply 2470 through an impedance match
circuit 2480. As indicated in FIG. 24, the two orthogonal
plasma currents coincide over the wafer surface and provide
15   more uniform coverage of plasma over the wafer surface.
This case is expected to find particularly advantageous use
for processing large wafers of diameters of 10 inches and
greater.

20   As in the case of FIG. 17, the case of FIG. 24 creates
two mutually orthogonal torroidal plasma current paths over
the wafer 120 for enhanced uniformity. The two orthogonal
torroidal or closed paths are separate and independently
powered as illustrated, but intersect in the process region
25   overlying the wafer, and otherwise do not interact or
otherwise divert or diffuse one another. In order to assure
separate control of the plasma source power applied to each
one of the orthogonal paths, the frequency of the respective
RF generators 180, 2470 of FIG. 24 are different, so that
30   the operation of the impedance match circuits 175, 2480 is
decoupled. For example, the RF generator 180 may produce an
RF signal at 11 MHz while the RF generator 2470 may produce
an RF signal at 12 MHz. Alternatively, independent
operation may be achieved by offsetting the phases of the
35   two RF generators 180, 2470.

41

FIG. 26 illustrates a variation of the case of FIG. 18 in which a modified rectangular enclosure 2650 that includes an insulating gap 2658 communicates with the chamber interior through the chamber side wall 105 rather than

5   through the ceiling 110. For this purpose, the rectangular enclosure 2650 has a horizontal top section 2652, a pair of downwardly extending legs 2654 at respective ends of the top section 2652 and a pair of horizontal inwardly extending legs 2656 each extending from the bottom end of a respective

10 one of the downwardly extending legs 2654 to a respective opening 2670, 2680 in the side wall 105.

FIG. 27 illustrates how a second rectangular tube enclosure 2710 including an insulating gap 2752 may be added

15 to the case of FIG. 26, the second tube enclosure 2710 being identical to the rectangular tube enclosure 2650 of FIG. 26 except that the rectangular tube enclosures 2650, 2710 are mutually orthogonal (or at least transverse to one another). The second rectangular tube enclosure communicates with the

20 chamber interior through respective openings through the side wall 105, including the opening 2720. Like the case of FIG. 25, the tube enclosures 2650 and 2710 produce mutually orthogonal torroidal plasma currents that coincide over the wafer surface to provide superior uniformity over a broader

25 wafer diameter. Plasma source power is applied to the interior of the tube enclosures through the respective pairs of side coil windings 165, 185 and 2450, 2460.

FIG. 28A illustrates how the side coils 165, 185, 2450,

30 2460 may be replaced (or supplemented) by a pair of mutually orthogonal interior coils 2820, 2840 lying within the external region 2860 surrounded by the two rectangular tube enclosures 2650, 2710. Each one of the coils 2820, 2840 produces the torroidal plasma current in a corresponding one

35 of the rectangular tube enclosures 2650, 2710. The coils 2820, 2840 may be driven completely independently at

42

different frequencies or at the same frequency with the same or a different phase. Or, they may be driven at the same frequency but with a phase difference (i.e., 90 degrees) that causes the combined torroidal plasma current to rotate at the source power frequency. In this case the coils 2820, 2840 are driven with the sin and cosine components, respectively, of a common signal generator 2880, as indicated in FIG. 28A. The advantage is that the plasma current path rotates azimuthally across the wafer surface at a rotational frequency that exceeds the plasma ion frequency so that non-uniformities are better suppressed than in prior art methods such as MERIE reactors in which the rotation is at a much lower frequency.

Referring now to FIG. 28B, radial adjustment of plasma ion density may be generally provided by provision of a pair of magnetic cylindrical cores 2892, 2894 that may be axially moved toward or away from one another within the coil 2820 and a pair of magnetic cylindrical cores 2896, 2898 that may be axially moved toward or away from one another within the coil 2840. As each pair of cores is moved toward one another, inductive coupling near the center of each of the orthogonal plasma currents is enhanced relative to the edge of the current, so that plasma density at the wafer center is generally enhanced. Thus, the center-to-edge plasma ion density may be controlled by moving the cores 2892, 2894, 2896, 2898.

FIG. 29 illustrates an alternative case of the invention in which the two tube enclosures 2650, 2710 are merged together into a single enclosure 2910 that extends 360 degrees around the center axis of the reactor that constitutes a single plenum. In the case of FIG. 29, the plenum 2910 has a half-dome lower wall 2920 and a half-dome upper wall 2930 generally congruent with the lower wall 2920. The plenum 2910 is therefore the space between the

43

upper and lower half-dome walls 2920, 2930. An insulating
gap 2921 may extend around the upper dome wall 2920 and/or
an insulating gap 2931 may extend around the lower dome wall
2930.   The plenum 2910 communicates with the chamber

5   interior through an annular opening 2925 in the ceiling 110
that extends 360 degrees around the axis of symmetry of the
chamber.

     The plenum 2910 completely encloses a region 2950 above
10   the ceiling 110.   In the case of FIG. 29, plasma source
power is coupled into the interior of the plenum 2910 by a
pair of mutually orthogonal coils 2960, 2965. Access to the
coils 2960, 2965 is provided through a vertical conduit 2980
passing through the center of the plenum 2910.   Preferably,
15   the coils 2960, 2965 are driven in quadrature as in the case
of FIG. 28 to achieve an azimuthally circulating torroidal
plasma current (i.e., a plasma current circulating within
the plane of the wafer. The rotation frequency is the
frequency of the applied RF power. Alternatively, the coils
20   2960, 2965 may be driven separately at different
frequencies. FIG. 30 is a top sectional view of the case of
FIG. 29. FIGS. 31A and 31B are front and side sectional
views, respectively, corresponding to FIG. 30.

25   The pair of mutually orthogonal coils 2960, 2965 may be
replaced by any number n of separately driven coils with
their winding axes disposed at 360/n degrees apart. For
example, FIG. 32 illustrates the case where the two coils
2960, 2965 are replace by three coils 3210, 3220, 3230 with
30   winding axes placed at 120 degree intervals and driven by
three respective RF supplies 3240, 3250, 3260 through
respective impedance match circuits 3241, 3251, 3261. In
order to produce a rotating torroidal plasma current, the
three windings 3210, 3220, 3230 are driven 120 degrees out
35   of phase from a common power source 3310 as illustrated in
FIG. 33. The cases of FIGS. 32 and 33 are preferred over

the case of FIG. 29 having only two coils, since it is felt
much of the mutual coupling between coils would be around
rather than through the vertical conduit 2980.

5   FIG. 34 illustrates a case in which the three coils are
outside of the enclosed region 2950, while their inductances
are coupled into the enclosed region 2950 by respective
vertical magnetic cores 3410 extending through the conduit
2980. Each core 3410 has one end extending above the
10   conduit 2980 around which a respective one of the coils
3210, 3220, 3230 is wound. The bottom of each core 3410 is
inside the enclosed region 2950 and has a horizontal leg.
The horizontal legs of the three cores 3410 are oriented at
120 degree intervals to provide inductive coupling to the
15   interior of the plenum 2910 similar to that provided by the
three coils inside the enclosed region as in FIG 32.

The advantage of the flattened rectangular tube
enclosures of the cases of FIGS. 18-28 is that the broad
20   width and relatively low height of the tube enclosure forces
the torroidal plasma current to be a wide thin belt of
plasma that more readily covers the entire surface of a
large diameter wafer. The entirety of the tube enclosure
need not be of the maximum width. Instead the outer section
25   of the tube enclosure farthest from the chamber interior may
be necked down, as discussed above with reference to the
case of FIG. 20. In this case, it is preferable to provide
focusing magnets 1870 at the transition corners between the
wide portion 1851 and the narrow section 1852 to force the
30   plasma current exiting the narrow portion 1852 to spread
entirely across the entire width of the wide section 1851.
If it is desired to maximize plasma ion density at the wafer
surface, then it is preferred that the cross-sectional area
of the narrow portion 1852 be at least nearly as great as
35   the cross-sectional area of the wide portion 1851. For
example, the narrow portion 1852 may be a passageway whose

45

height and width are about the same while the wide portion
1851 may have a height that is less than its width.

The various cases described herein with air-core coils
5 (i.e., coils without a magnetic core) may instead employ
magnetic-cores, which can be the open-magnetic-path type or
the closed-magnetic-core type illustrated in the
accompanying drawings. Furthermore, the various cases
described herein having two or more torroidal paths driven
10 with different RF frequencies may instead be driven with
same frequency, and with the same or different phases.

FIG. 35 is a version of the case of FIG. 17 in which
the mutually transverse hollow conduits are narrowed as in
15 the case of FIG. 20.

FIG. 36 is a version of the case of FIG. 24 but
employing a pair of magnetic cores 3610, 3620 with
respective windings 3630, 3640 therearound for connection to
20 respective RF power sources.

FIG. 37 is a case corresponding to that of FIG. 35 but
having three instead of two reentrant conduits with a total
of six reentrant ports to the chamber. Having a number of
25 symmetrically disposed conduits and reentrant ports greater
than two (as in the case of FIG. 37) is believed to be
particularly advantageous for processing wafers of diameter
of 300 mm and greater.

30 FIG. 38 is a case corresponding to that of FIG. 38 but
having three instead of two reentrant conduits with a total
of six reentrant ports to the chamber.

FIG. 39 is a case corresponding to that of FIG. 35 in
35 which the external conduits join together in a common plenum
3910.

46

FIG. 40 is a case corresponding to that of FIG. 36 in which the external conduits join together in a common plenum 4010.

FIG. 41 is a case corresponding to that of FIG. 37 in which the external conduits join together in a common plenum 4110.

FIG. 42 is a case corresponding to that of FIG. 38 in which the external conduits join together in a common plenum 4210.

FIG. 43 is a case corresponding to that of FIG. 17 in which the external conduits join together in a common plenum 4310.

Advantageous Features:

Constricting the torroidal plasma current in the vicinity of the wafer not only improves etch selectivity but at the same time increases the etch rate by increasing the plasma ion density. It is believed no prior reactor has increased etch selectivity by the same mechanism that increases etch rate or plasma ion density over the workpiece.

Improving etch selectivity by constricting the torroidal plasma current in the vicinity of the wafer or workpiece can be achieved in the invention in any one of several ways. One way is to reduce the pedestal-to-ceiling or wafer-to-ceiling height. Another is to introduce a gas distribution plate or showerhead over the wafer that constricts the path of the torroidal plasma ion current. Another way is to increase the RF bias power applied to the wafer or workpiece. Any one or any combination of the

47

foregoing ways of improving etch selectivity may be chosen
by the skilled worker in carrying out the invention.

Etch selectivity may be further improved in the
invention by injecting the reactive process gases locally
(i.e., near the wafer or workpiece) while injecting an inert
diluent gas (e.g., Argon) remotely (i.e., into the conduit
or plenum). This may be accomplished by providing a gas
distribution plate or showerhead directly over and facing
the workpiece support and introducing the reactive process
gas exclusively (or at least predominantly) through the
showerhead. Concurrently, the diluent gas is injected into
the conduit well away from the process region overlying the
wafer or workpiece. The torroidal plasma current thus
becomes not only a source of plasma ions for reactive ion
etching of materials on the wafer but, in addition, becomes
an agent for sweeping away the reactive process gas species
and their plasma-dissociated progeny before the plasma-
induced dissociation process is carried out to the point of
creating an undesirable amount of free fluorine. This
reduction in the residence time of the reactive process gas
species enhances the etch selectivity relative to
photoresist and other materials, a significant advantage.

Great flexibility is provided in the application of RF
plasma source power to the torroidal plasma current. As
discussed above, power is typically inductively coupled to
the torroidal plasma current by an antenna. In many cases,
the antenna predominantly is coupled to the external conduit
or plenum by being close or next to it. For example, a coil
antenna may extend alongside the conduit or plenum.
However, in other cases the antenna is confined to the
region enclosed between the conduit or plenum and the main
reactor enclosure (e.g., the ceiling). In the latter case,
the antenna may be considered to be "under" the conduit
rather than alongside of it. Even greater flexibility is

48

afford by cases having a magnetic core (or cores) extending through the enclosed region (between the conduit and the main chamber enclosure) and having an extension beyond the enclosed region, the antenna being wound around the core's extension. In this case the antenna is inductively coupled via the magnetic core and therefore need not be adjacent the torroidal plasma current in the conduit. In one such case, a closed magnetic core is employed and the antenna is wrapped around the section of the core that is furthest away from the torroidal plasma current or the conduit. Therefore, in effect, the antenna may be located almost anywhere, such as a location entirely remote from the plasma chamber, by remotely coupling it to the torroidal plasma current via a magnetic core.

Finally, plasma distribution over the surface of a very large diameter wafer or workpiece is uniform. This is accomplished in one case by shaping the torroidal plasma current as a broad plasma belt having a width preferably exceeding that of the wafer. In another case, uniformity of plasma ion density across the wafer surface is achieved by providing two or more mutually transverse or orthogonal torroidal plasma currents that intersect in the process region over the wafer. The torroidal plasma currents flow in directions mutually offset from one another by 360/n. Each of the torroidal plasma currents may be shaped as a broad belt of plasma to cover a very large diameter wafer. Each one of the torroidal plasma currents may be powered by a separate coil antenna aligned along the direction of the one torroidal plasma current. In one preferred case, uniformity is enhanced by applying RF signals of different phases to the respective coil antennas so as to achieve a rotating torroidal plasma current in the process region overlying the wafer. In this preferred case, the optimum structure is one in which the torroidal plasma current flows in a circularly continuous plenum communicating with the

49

main chamber portion through a circularly continuous annular opening in the ceiling or side wall. This latter feature allows the entire torroidal plasma current to rotate azimuthally in a continuous manner.

5

Controlling Radial Distribution of Plasma Ion Density:
FIG. 44 illustrates a plasma reactor similar to that illustrated in FIG. 17A having a pair of orthogonal external
10 reentrant tubes 150-1, 150B2. RF power is coupled into the tubes by respective annular magnetic cores 1015-1, 1015-2 excited by respective RF-driven coils 170-1, 170-2, as described above with reference to FIG. 17A. However, in FIG. 44 the external tubes 150-1, 150-2 are rectangular as
15 in FIG. 24 rather than being round in cross-sectional shape. Moreover, the horizontal section of the lower tube 150-1 is not flat but rather has a dip 4410 at its middle. The dip 4410 permits the upper external tube 150-2 to nest closer to the reactor ceiling 110. This feature shortens the path
20 length in the upper tube 150-2, thereby reducing plasma losses in the upper tube 150-2. In fact, the shape of the dip 4410 may be selected to at least nearly equalize the path length through the upper and lower external tubes 150-1, 150-2. The reactor of FIG. 44, like the reactors of
25 FIGS. 2 and 26, has a gas distribution plate 210 on the ceiling 110 (or forming the ceiling 110 itself) and overlying the wafer 120.

The dip 4410 is limited in that a vertical space
30 remains between the top surface of the ceiling 110 and a bottom corner 4422 formed on the lower tube 150-1 at the apex of the dip 4410. The vertical space accommodates an electromagnet assembly 4430 that enhances plasma ion density over the center of the wafer 120. The electromagnet
35 assembly 4430 includes a narrow elongate cylindrical pole piece 4440 formed of a magnetizable metal such as iron or

50

steel (for example) and a coil 4450 of insulated conductive
wire (e.g., copper wire) wrapped around the pole piece 4440.
The cylindrical axis of the pole piece 4440 coincides with
the axis of symmetry of the cylindrical chamber 100, so that
the axis of the pole piece 4440 intersects the center of the
wafer 120. The coil 4450 may be wrapped directly on the
pole piece 4440 or, as illustrated in FIG. 45, may be
wrapped around a mandril 4460 encircling the pole piece
4440. FIG. 45 shows that the coil 4450 may be wrapped
around a section 4440-1 of the pole piece 4440 that extends
above the ceiling 110. The lower section 4440-2 of the pole
piece 4440 that is inside the ceiling 110 terminates within
the gas manifold 220 of the gas distribution plate 210.

        For efficiency, it is desirable to place the source of
the plasma-confining magnetic field as close to the plasma
as practical without disturbing gas flow within the gas
distribution plate 210. For this purpose, the portion of
the lower pole piece section 4440-2 that is inside the gas
manifold 220 is a very narrow cylindrical end piece 4470
that terminates the pole piece 4440. The end piece 4470
extends the magnetic field lines of the pole piece 4440 near
the bottom of the gas distribution plate to enhance the
effect of the magnetic field on the plasma. The diameter of
the end piece 4470 is sufficiently reduced so that it does
not appreciably interfere with gas flow within the gas
manifold 210. Moreover, such a reduced diameter brings the
peak of the radial component of the magnetic field nearer
the center axis.

        FIG. 46 illustrates one case of the end piece 4470
having a tapered bottom 4475 terminated in a nipple 4477.
FIG. 47 illustrates a case of the end piece 4470 in which
the bottom 4476 is flat. FIG. 48 illustrates a case of the
end piece 4470 in which the bottom 4478 is round.

51

In one implementation, pole piece 4440 has a diameter
of about 3.5 cm (such that the diameter of the approximately
60 turn coil 4450 is about 6 cm) and is about 12 cm long.
The pole piece 4440 is extended about 2 cm (to a total of
5   about 14 cm) with a smaller diameter extension of about 1 cm
diameter. The bottom of the extension region of the pole
piece 4440 is about 1.5 cm from the top of the plasma
region. The material composition of pole piece 4440 is
selected to have sufficiently high permeability (e.g., μr >
10   or = 100) and high saturation flux density (e.g. Bsat > 1000
gauss) to maximize the magnetic flux density in the region
below the pole piece 4440 with minimum magnetizing force and
current. Note that because the magnetic path is "open" with
pole piece 4440 (not closed within the pole piece), the
15   effective permeability is reduced relative to the material
permeability. Depending on the length/diameter ratio of the
pole piece 4440, the μr "effective" is typically reduced to
on the order of 10.

20   An optional shield 4479 of magnetic material such as
iron shields plasma in the pair of tubes 150-1, 150-2 from
the D.C. magnetic field of the electromagnet assembly 4430.
The shield 4479 includes an overhead plate 4479a and a
cylindrical skirt 4479b.
25

In the case of the gas distribution plate 210
illustrated in FIG. 45, a top plate 4480 is divided into
radially inner and outer sections 4480a, 4480b, each having
many small gas flow holes 4481 extending through it, the
30   inner and outer sections having annular flanges 4482-1,
4482-2, 4482-3, 4482-4, forming vertical walls supporting
the bottom surface of the ceiling 210 and forming therewith
inner and outer gas manifolds 4483a, 4483b separated by a
wall formed by the annular flanges 4482-2, 4482-3. In one
35   case, there is no wall between the inner and outer gas

52

manifolds, so as to avoid any discontinuity in gas
distribution within the chamber that such a wall may cause.
A gas mixing layer 4484 below the top plate 4480 diverts gas
flow from a purely vertical flow direction and thereby

5   induces multi-directional (or turbulent) gas flow that
improves uniform mixing of gases of different molecular
weights. Such diverting of the gas flow from a purely
downward flow direction has the added benefit of suppressing
high velocity gas flow effects, in which high velocity gas

10 flow through gas distribution plate orifices directly over
the wafer would form localized concentrations of process gas
on the wafer surface that disrupt process uniformity.
Suppression of high velocity gas flow effects enhances
uniformity.

15

      The gas mixing layer 4484 may consist of metal or
ceramic foam of the type well-known in the art. Or, as
shown in FIG. 49, the gas mixture layer 4484 may consist of
plural perforation plates 4484-1, 4484-2 each having many

20 small gas orifices drilled through it, the holes in one
perforation plate being offset from the holes in the other
perforation plate. A bottom plate 4485 of the gas
distribution plate 210 has many sub-millimeter gas injection
holes 4486 drilled through it with large counterbored holes

25 4487 at the top of the bottom plate 4485. In one example,
the sub-millimeter holes were between 10 and 30 mils in
diameter, the counterbored holes were about 0.06 inch in
diameter and the bottom plate 4485 had a thickness of about
0.4 inch. Inner and outer gas feed lines 4490, 4492 through

30 the ceiling 110 furnish gas to the inner and outer top
plates 4480a, 4480b, so that gas flow in radially inner and
outer zones of the chamber may be controlled independently
as a way of adjusting process uniformity.

35   It is believed that the radial component of the D.C.
magnetic field produced by the electromagnet assembly 4430

53

affects the radial distribution of plasma ion density, and
that it is this radial component of the magnetic field that
can be exploited to enhance plasma ion density near the
center of the chamber. It is believed that such enhancement

5   of plasma ion density over the wafer center arises from the
interaction of the D.C. magnetic field radial component with
the plasma sheath electric field at the wafer surface
producing azimuthal plasma currents tending to confine
plasma near the wafer center. In absence of the D.C.

10 magnetic field, the phenomenon of a reduced plasma ion
density at the center of the chamber extends over a very
small circular zone confined closely to the center of the
wafer 120, because in general the reactor of FIG. 44 tends
to have an exceptionally uniform plasma ion density even in

15 absence of a correcting magnetic field. Therefore,
correction of the center-low plasma ion density distribution
requires a D.C. magnetic field having a relatively large
radial component very near the center of the chamber or
wafer 120. The small diameter of the magnetic pole piece

20 4440 produces a magnetic field having a large radial
component very close to the center of the wafer 120 (or
center of the chamber). In accordance with conventional
practice, the center is the axis of symmetry of the
cylindrical chamber at which the radius is zero. FIG. 51

25 illustrates the distribution of the magnetic field in an
elevational view of the processing region over the wafer 120
between the wafer 120 and the gas distribution plate 210.
The vectors in FIG. 51 are normalized vectors representing
the direction of the magnetic field at various locations.

30 FIG. 52 illustrates the magnetic flux density of the radial
component of the magnetic field as a function of radial
location, one curve representing the radial field flux
density near the bottom surface of the gas distribution
plate 210 and the other curve representing the radial field

35 flux density near the surface of the wafer 120. The peak of
the flux density of the radial magnetic field component is

54

very close to the center, namely at about a radius of only
one inch both at the ceiling and at the wafer. Thus, the
radial component of the magnetic field is tightly
concentrated near the very small diameter region within
5   which the plasma ion density tends to be lowest. Thus, the
distribution of the radial component of the D.C. magnetic
field produced by the electromagnet assembly 4430 generally
coincides with the region of low plasma ion density near the
center of the chamber.
10

As mentioned above, it is felt that the radial
component of the D.C. magnetic field interacts with the
vertically oriented electric field of the plasma sheath near
the wafer center to produce an azimuthally directed force
15   that generally opposes radial travel of plasma.   As a
result, plasma near the center of the wafer is confined to
enhance processing within that region.

A basic approach of using the electromagnet assembly
20   4430 in an etch reactor is to find a D.C. current flow in
the coil that produces the most uniform etch rate radial
distribution across the wafer surface, typically by
enhancing plasma ion density at the center. This is the
likeliest approach in cases in which the wafer-to-ceiling
25   gap is relatively small (e.g., one inch), since such a small
gap typically results in a center-low etch rate distribution
on the wafer. For reactors having a larger gap (e.g., two
inches or more), the etch rate distribution may not be
center low, so that a different D.C. current may be needed.
30   Of course, the electromagnet assembly 4430 is not confined
to applications requiring improved uniformity of plasma ion
density across the wafer surface. Some applications of the
electromagnet assembly may require an electromagnet coil
current that renders the plasma ion density less uniform.
35   Such applications may involve, for example, cases in which a
field oxide thin film layer to be etched has a non-uniform

55

thickness distribution, so that uniform results can be obtained only by providing nonuniform plasma ion density distribution that compensates for the nonuniform field oxide thickness distribution. In such a case, the D.C. current in
5   the electromagnet assembly can be selected to provide the requisite nonuniform plasma ion distribution.

As shown in FIG. 45, the plasma reactor may include a set of integrated rate monitors 4111 that can observe the
10 etch rate distribution across the wafer 120 during the etch process. Each monitor 4111 observes the interference fringes in light reflected from the bottom of contact holes while the holes are being etched. The light can be from a laser or may be the luminescence of the plasma. Such real
15 time observation can make it possible to determine changes in etch rate distribution across the wafer that can be instantly compensated by changing the D.C. current applied to the electromagnet assembly 4430.

20   FIG. 53 shows one way of independently controlling process gas flow to the inner and outer gas feed lines 4490, 4492. In FIG. 53, one set of gas flow controllers 5310, 5320, 5330 connected to the inner gas feed line 4490 furnish, respectively, argon, oxygen and a fluoro-carbon
25 gas, such as C4F6, to the inner gas feed line 4490. Another set of gas flow controllers 5340, 5350, 5360 furnish, respectively, argon, oxygen and a fluoro-carbon gas, such as C4F6, to the outer gas feed line 4492.   FIG. 54 shows another way of independently controlling process gas flow to
30 the inner and outer gas feed lines 4490, 4492. In FIG. 54, a single set of gas flow controllers 5410, 5420, 5430 furnishes process gases (e.g., argon, oxygen and a fluoro-carbon gas) to a gas splitter 5440. The gas splitter 5440 has a pair of gas or mass flow controllers (MFC's) 5442,
35 5444 connected, respectively, to the inner and outer gas feed lines 4490, 4492. In addition, optionally another gas

flow controller 5446 supplies purge gas such as Argon or
Neon to the outer gas feed line 4492.

One problem in processing a large diameter wafer is
5   that the torroidal or reentrant plasma current must spread
out evenly over the wide surface of the wafer. The tubes
150 typically are less wide than the process area. The need
then is to broaden the plasma current to better cover a wide
process area as it exits a port 155 or 160. As related
10   problem is that the reactor of FIG. 44 (or any of the
reactors of FIGS. 1-43) can experience a problem of non-
uniform plasma ion density and consequent "hot spot" or
small region 5505 of very high plasma ion density near a
port 155 or 160 of the reentrant tube 150, as shown in FIG.
15   55A. Referring to FIGS. 55A-56B, these problems are
addressed by the introduction of a plasma current flow
splitter 5510 at the mouth of each port (e.g., the port 155
as shown in FIG. 55A). The splitter 5510 tends to force the
plasma current to widen while at the same time reducing
20   plasma ion density in the vicinity of the region 5505 where
a hot spot might otherwise form. The tube 150 can have a
widened termination section 5520 at the port 155, the
termination section 5520 having a diameter nearly twice as
great as that of the remaining portion of the tube 150. The
25   plasma current flow splitter 5510 of FIG. 55A is triangular
in shape, with one apex facing the interior of the tube 150
so as to force the plasma current flowing into the chamber
100 from the tube 150 to spread out so as to better fill the
larger diameter of the termination section 5520. This
30   current-spreading result produced by the triangular splitter
5510 tends to widen the plasma current and reduces or
eliminates the "hot spot" in the region 5505.

The optimum shape of the splitter 5510 depends at least
35   in part upon the separation distance S between the centers
of opposing ports 155, 160. If the splitter is too long in

57

the direction of plasma flow (i.e., the vertical direction
in FIG. 55A), then current flow along the divided path tends
to be unbalanced, with all current flowing along one side of
the splitter 5510. On the other hand, if the splitter 5510
5   is too short, the two paths recombine before the plasma
current appreciably widens.

For example, in a chamber for processing a 12-inch
diameter wafer, the separation distance S can be about 20.5
10   inches, with a tube width w of 5 inches, a tube draft d of
1.75 inches and an expanded termination section width W of 8
inches. In this case, the juxtaposition of the port 155
relative to the 12 inch wafer would be as shown in the plan
view of FIG. 56C. In this particular example, the height h
15   of the splitter 5510 should be about 2.5 inches, with the
angle of the splitter's apex 5510a being about 75 degrees,
as shown in FIG. 57. In addition, the length L of the
termination section 5520 should equal the height h of the
splitter 5510.
20

On the other hand, for a separation distance S of 16.5
inches, an optimum splitter 5510' is illustrated in FIG. 58.
The angle of the splitter apex in this case is preferably
about 45 degrees, the triangular portion being terminated in
25   a rectangular portion having a width of 1.2 inches and a
length such that the splitter 5510' has a height h of 2.5
inches. The height and apex angle of the splitter 5510 or
5510' must be sufficient to reduce plasma density in the
region 5505 to prevent formation of a hot spot there.
30   However, the height h must be limited in order to avoid
depleting plasma ion density at the wafer center.

FIGS. 59A and 59B illustrate splitters for solving the
problem of plasma ion density non-uniformity near the
35   entrance ports of a reentrant tube 2654 in which plasma
current flow through each port is in a horizontal direction

58

through the chamber side wall 105, as in the reactor of FIG. 26. Each splitter 5910 has its apex 5910a facing the port 2680.

5   FIGS. 60, 61 and 62 illustrate an implementation like that of FIG. 17A, except that the chamber side wall 105 is rectangular or square and the vertically facing ports 140-1, 140-2, 140-3 and 140-4 through the ceiling 110 are located over respective corners 105a, 105b, etc. of the rectangular

10   or square side wall 105. A floor 6020 in the plane of the wafer 120 faces each port and, together with the corner-forming sections of the rectangular side wall 105, forces incoming plasma current to turn toward the processing region overlying the wafer 120. In order to reduce or eliminate a

15   hot spot in plasma ion density in the region 6030, a triangular plasma current flow splitter 6010 is placed near each respective corner 105a, 105b, etc., with its apex 6010a facing that corner. In the implementation of FIG. 61, the splitter apex 6010a is rounded, but in other implementations

20   it may be less rounded or actually may be a sharp edge. FIG. 63 illustrates a portion of the same arrangement but in which the edge 6010b of the splitter 6010 facing the wafer 120 is located very close to the wafer 120 and is arcuately shaped to be congruent with the circular edge of the wafer

25   120. While the splitter 6010 of FIG. 60 extends from the floor 6020 to the ceiling 110, FIG. 64 illustrates that the height of the splitter 6010 may be less, so as to allow some plasma current to pass over the splitter 6010.

30   As will be discussed in greater detail below with respect to certain working examples, the total path length traversed by the reentrant plasma current affects plasma ion density at the wafer surface. This is because shorter path length places a higher proportion of the plasma within the

35   processing region overlying the wafer, reduces path length-dependent losses of plasma ions and reduces surface area

59

losses due to plasma interaction with the reentrant tube
surface. Therefore, the shorter length tubes (corresponding
to a shorter port separation distance S) are more efficient.
On the other hand, a shorter separation distance S affords

5   less opportunity for plasma current flow separated at its
center by the triangular splitter 5510 to reenter the center
region after passing the splitter 5510 and avoid a low
plasma ion density at the wafer center. Thus, there would
appear to be a tradeoff between the higher efficiency of a

10   smaller port separation distance S and the risk of
depressing plasma ion density at the wafer center in the
effort to avoid a plasma hot spot near each reentrant tube
port.

15   This tradeoff is ameliorated or eliminated in the case
of FIGS. 65A, 65B and 66, by using a triangular splitter
6510 that extends at least nearly across the entire width W
of the termination section 5520 of the port and is shaped to
force plasma current flow away from the inner edge 6610 of

20   the port and toward the outer edge 6620 of the port. This
feature leaves the port separation distance S unchanged (so
that it may be as short as desired), but in effect lengthens
the plasma current path from the apex 6510a of the splitter
to the center of the wafer 120. This affords a greater

25   opportunity for the plasma current flow split by the
splitter 6510 to rejoin at its center before reaching the
wafer or center of the wafer. This feature better avoids
depressing plasma ion density at the wafer center while
suppressing formation of plasma hot spots at the reentrant

30   tube ports.

          As illustrated in FIGS. 65A, 65B and 66, each splitter
6510 presents an isoceles triangular shape in elevation
(FIG. 65B) and a rectangular shape from the top (FIG. 65A).

35   The side view of FIG. 66 reveals the sloping back surface
6610c that extends downwardly toward the outer edge 6620 of

the port. It is the sloping back surface 6610c that forces
the plasma current toward the back edge 6620 thereby
effectively lengthening the path from the top of the apex
6510a to the wafer center, which is the desired feature as
5   set forth above. The rectangular opening of the port 150 is
narrowed in the radial direction (the short dimension) by
the sloped wall or sloping back surface 6610b from about 2"
at top to about 3/4" at the bottom. This pushes the inner
port edge about 1-1/4" radially farther from the wafer (thus
10   achieving the desired increase in effective port separation
distance). In addition, the port 150 has the full
triangular splitter 6510 in the azimuthal direction (the
long or 8" wide dimension of the opening 150).

15   The plasma current splitter 5510 or 6510 may have
coolant passages extending within it with coolant ports
coupled to similar ports in the reactor body to regulate the
temperature of the splitter. For this purpose, the plasma
current splitter 5510 or 6510 is formed of metal, since it
20   easily cooled and is readily machined to form internal
coolant passages. However, the splitter 5510 or 6510 may
instead be formed of another material such as quartz, for
example.

25   FIG. 67 illustrates another way of improving plasma
uniformity in the torroidal source reactor of FIG. 24 by
introducing a set of four annular electromagnets 6710, 6720,
6730, 6740 along the periphery of the reactor, the windings
of each electromagnet being controlled by a magnet current
30   controller 6750. The electric currents in the four
electromagnets may be driven in any one of three modes:
(1) in a first mode, a sinusoidal mode, the coils are driven
at the same low frequency current in phase quadrature to
produce a magnetic field that rotates about the axis of
35   symmetry of the reactor at the low frequency of the source;
(2) in a second mode, a configurable magnetic field mode,

the four electromagnets 6710, 6720, 6730, 6740 are grouped
into opposing pairs of adjacent electromagnets, and each
pair is driven with a different D.C. current to produce a
magnetic field gradient extending diagonally between the
5   opposing pairs of adjacent electromagnets, and this grouping
is rotated so that the magnetic field gradient is rotated to
isotropically distribute its effects over the wafer;
(3) in a third mode, the four electromagnets are all driven
with the same D.C. current to produce a cusp-shaped magnetic
10 field having an axis of symmetry coinciding generally with
the axis of symmetry of the reactor chamber.

As shown in FIG. 1, a pumping annulus is formed between
the cylindrical wafer support pedestal 115 and the
15 cylindrical side wall 105, gases being evacuated via the
pumping annulus by the vacuum pump 135. Plasma current flow
between the opposing ports of each reentrant tube 150 can
flow through this pumping annulus and thereby avoid flowing
through the processing region between the wafer 120 and the
20 gas distribution plate 210. Such diversion of plasma
current flow around the process region can occur if the
chamber pressure is relatively high and the wafer-to-ceiling
gap is relatively small and/or the conductivity of the
plasma is relatively low. To the extent this occurs, plasma
25 ion density in the process region is reduced. This problem
is solved as shown in FIGS. 68 and 69 by the introduction of
radial vanes 6910, 6920, 6930, 6940 blocking azimuthal
plasma current flow through the pumping annulus. In one
implementation, the vanes 6910, 6920, 6930, 6940 extend up
30 to but not above the plane of the wafer 120, to allow
insertion and removal of the wafer 120. However, in another
implementation the vanes may retractably extend above the
plane of the wafer to better confine the plasma current flow
within the processing region overlying the wafer 120. This
35 may be accomplished by enabling the wafer support pedestal
115 to move up and down relative to the vanes, for example.

62

In either case, the vanes 6910, 6920, 6930, 6940 prevent plasma current flow through the pumping annulus, and, if the vanes can be moved above the plane of the wafer 120, they also reduce plasma current flow through the upper region

5   overlying the pumping annulus. By thus preventing diversion of plasma current flow away from the processing region overlying the wafer, not only is plasma ion density improved in that region but process stability is also improved.

10   As mentioned previously herein, the magnetic core used to couple RF power to each reentrant tube 150 tends to crack or shatter at high RF power levels. It is believed this problem arises because magnetic flux is not distributed uniformly around the core. Generally, one winding around

15   the core has a high current at high RF power levels. This winding can be, for example, a secondary winding that resonates the primary winding connected to the RF generator. The secondary winding is generally confined to a narrow band around the core, magnetic flux and heating being very

20   high within this band **and** much lower elsewhere in the core. The magnetic core must have a suitable permeability (e.g., a permeability between about 10 and 200) to avoid self-resonance at high frequencies. A good magnetic core tends to be a poor heat conductor (low thermal conductivity) and

25   be readily heated (high specific heat), and is therefore susceptible to localized heating. Since the heating is localized near the high current secondary winding and since the core tends to be brittle, it cracks or shatters at high RF power levels (e.g., 5 kiloWatts of continuous power).

30
      This problem is solved in the manner illustrated in FIGS. 70 through 74 by more uniformly distributing RF magnetic flux density around the annular core. FIG. 70 illustrates a typical one of the magnetic cores 1015 of FIG.

35   17A. The core 1015 is formed of a high magnetic

permeability material such as ferrite. The primary winding
170 consists of about two turns of a thin copper band
optionally connected through an impedance match device 175
to the RF generator 180. High current flow required for
5   high magnetic flux in the core 1015 occurs in a resonant
secondary winding 7010 around the core 1015. Current flow
in the secondary winding 7010 is about an order of magnitude
greater than current flow in the primary winding. In order
to uniformly distribute magnetic flux around the core 1015,
10 the secondary winding 7010 is divided into plural sections
7010a, 7010b, 7010c, etc., that are evenly distributed
around the annular core 1015. The secondary winding
sections 7010a, etc., are connected in parallel. Such
parallel connection is facilitated as illustrated in FIGS.
15 71A and 71B by a pair of circular copper buses 7110, 7120
extending around opposite sides of the magnetic core 1015.
Opposing ends of each of the secondary windings 7010a,
7010b, etc., are connected to opposite ones of the two
copper buses 7110, 7120. The copper buses 7110, 7120 are
20 sufficiently thick to provide an extremely high conductance
and low inductance, so that the azimuthal location of any
particular one of the secondary winding sections 7010a,
7010b, etc. makes little or no difference, so that all
secondary winding sections function as if they were
25 equidistant from the primary winding. In this way, magnetic
coupling is uniformly distributed around the entire core
1015.

    Because of the uniform distribution of magnetic flux
30 achieved by the foregoing features, the primary winding may
be placed at any suitable location, typically near a
selected one of the plural distributed secondary winding
sections 7110a, 7110b, 7110c, etc. However, in one
implementation, the primary winding is wrapped around or on
35 a selected one of the plural distributed secondary winding
sections 7110a, 7110b, 7110c, etc.

FIG. 72 is a representation of the distributed parallel inductances formed by the parallel secondary winding sections 7010a, 7010b, etc., and FIG. 73 shows the circular topology of these distributed inductances. In order to provide resonance at the frequency of the RF generator 180, plural distributed capacitors 7130 are connected in parallel across the two copper buses 7110, 7120. The plural capacitors 7030 are distributed azimuthally around the magnetic core 1015. Each capacitor 7030 in one implementation was about 100 picoFarads. The equivalent circuit of the distributed inductances and capacitances associated with the secondary winding 7010 is illustrated in FIG. 24.

Referring to FIG. 71B, the secondary winding sections 7010a, 7010b, etc., can have the same number of turns. In the case of FIG. 71B, there are six secondary winding sections 7010a-7010f, each section having three windings. The skilled worker can readily select the number of secondary winding sections, the number of windings in each section and the capacitance of the distributed capacitors 7030 to achieve resonance at the frequency of the RF generator 180. The copper band stock used to form the primary and secondary windings around the core 1015 can be, for example, 0.5 inch wide and 0.020 inch thick copper stripping. The two copper buses 7110, 7120 are very thick (e.g., from 0.125 inch to 0.25 inch thick) and wide (e.g., 0.5 inch wide) so that they form extremely low resistance, low inductance current paths. The core 1015 may consist of a pair of stacked 1 inch thick ferrite cores with a 10 inch outer diameter and an 8 inch inner diameter. Preferably, the ferrite core 1015 has a magnetic permeability μ=40. The foregoing details are provided by way of example only, and any or all of the foregoing values may require modification

for different applications (e.g., where, for example, the frequency of the RF generator is modified).

We have found that the feature of distributed inductances illustrated in FIGS. 71A and 71B solves the problem of breakage of the magnetic core experienced at sustained high RF power levels (e.g., 5 kiloWatts).

FIG. 75 illustrates the equivalent circuit formed by the core and windings of FIGS. 71A and 71B. In addition to the primary and secondary windings 170 and 7010 around the core 1015, FIG. 75 illustrates the equivalent inductive and capacitive load presented by the plasma inductively coupled to the core 1015. The case of FIGS. 70-75 is a transformer coupled circuit. The purpose of the secondary winding 7010 is to provide high electric current flow around the magnetic core 1015 for enhanced power coupling via the core. The secondary winding 7010 achieves this by resonating at the frequency of the RF generator. Thus, the high current flow and power coupling via the magnetic core 1015 occurs in the secondary winding 7010, so that virtually all the heating of the core 1015 occurs at the secondary winding 7010. By thus distributing the secondary winding 7010 around the entire circumference of the core 1015, this heating is similarly distributed around the core to avoid localized heating and thereby prevent shattering the core at high RF power levels.

The distributed winding feature of FIGS. 71A and 71B can be used to implement other circuit topologies, such as the auto transformer circuit of FIG. 76. In the auto transformer circuit of FIG. 76, the winding 7010 around the core 1015 is distributed (in the manner discussed above with reference to FIGS. 70-74) and has a tap 7610 connected through the impedance match circuit 175 to the RF generator 180. The distributed capacitors 7030 provide resonance (in the manner discussed above). As in FIG. 70, the core 7010

66

is wrapped around the reentrant tube 150 so that power is inductively coupled into the interior of the tube 150. The circuit topologies of FIGS. 75 and 76 are only two examples of the various topologies that can employ distributed

5   windings around the magnetic core 1015.

In one implementation, the impedance match circuits 175a, 175b employed frequency tuning in which the frequency of each RF generator 180a, 180b is controlled in a feedback

10   circuit in such a way as to minimize reflected power and maximize forward or delivered power. In such an implementation, the frequency tuning ranges of each of the generators 180a, 180b are exclusive, so that their frequencies always differ, typically on the order of a 0.2

15   to 2 MHz difference. Moreover, their phase relationship is random. This frequency difference can improve stability. For example, instabilities can arise if the same frequency is used to excite plasma in both of the orthogonal tubes 150-1, 150-2. Such instabilities can cause the plasma

20   current to flow through only three of the four ports 155, 160, for example. This instability may be related to the phase difference between the torroidal plasma currents in the tubes. One factor facilitating plasma stability is isolation between the two plasma currents of the pair of

25   orthogonal tubes 150-1, 150-2. This isolation is provided mainly by the plasma sheaths of the two plasma currents. The D.C. break or gap 152 of each of the reentrant tubes 150-1, 150-2 also enhances plasma stability.

30   While the D.C. break or gap 152 in each of the orthogonal tubes is illustrated in FIG. 44 as being well-above the chamber ceiling 110, it may in fact be very close to or adjacent the ceiling. Such an arrangement is employed in the implementation of FIG. 77, in which the case of FIG.

35   55A is modified so that the termination section 5520 electrically floats so that its potential follows

67

oscillations of the plasma potential. This solves a problem that can be referred to as a "hollow cathode" effect near each of the ports 155, 160 that creates non-uniform plasma distribution. This effect may be referred to as an electron multiplication cavity effect. By permitting all of the conductive material near a port to follow the plasma potential oscillations, the hollow cathode effects are reduced or substantially eliminated. This is achieved by electrically isolating the termination section 5520 from the grounded chamber body by locating a D.C. break or gap 152' at the juncture between the reentrant tube termination section 5520 and the top or external surface of the ceiling 110. (The gap 152' may be in addition to or in lieu of the gap 152 of FIG. 44.) The gap 152' is filled with an insulative annular ring 7710, and the termination section 5520 of FIG. 77 has a shoulder 7720 resting on the top of the insulative ring 7710. Moreover, there is an annular vacuum gap 7730 of about 0.3 to 3 mm width between the ceiling 110 and the termination section 5520. In one implementation, the tube 150 and the termination section 5520 are integrally formed together as a single piece. The termination section 5520 is preferably formed of metal so that internal coolant passages may be formed therein.

FIGS. 44-77 illustrate cases in which the uniformity control magnet is above the processing region. FIG. 78 illustrates that the magnet pole 4440 may be placed below the processing region, or under the wafer support pedestal 115.

Working Examples:

An etch process was conducted on blanket oxide wafers at a chamber pressure of 40 mT, 4800 watts of 13.56 MHz RF bias power on the wafer pedestal and 1800 Watts of RF source power applied to each reentrant tube 150 at 11.5 MHz and

68

12.5 MHz, respectively. The magnetic field produced by the electromagnet assembly 4430 was set at the following levels in successive steps: (a) zero, (b) 6 Gauss and (c) 18 Gauss (where the more easily measured axial magnetic field
5   component at the wafer center was observed rather than the more relevant radial component). The observed etch rate distribution on the wafer surface was measured, respectively, as (a) center low with a standard deviation of about 2% at zero Gauss, (b) slightly center fast with a
10 standard deviation of about 1.2 % at 6 Gauss, and (c) center fast with a standard deviation of 1.4%. These examples demonstrate the ability to provide nearly ideal compensation (step b) and the power to overcompensate (step c).

15   To test the effective pressure range, the chamber pressure was increased to 160 mT and the electromagnet's field was increased in three steps from (a) zero Gauss, to (b) 28 Gauss and finally to (c) 35 Gauss (where the more easily measured axial magnetic field component at the wafer
20 center was observed rather than the more relevant radial component). The observed etch rate was, respectively, (a) center slow with a standard deviation of about 2.4%, center fast with a standard deviation of about 2.9% and center fast with a standard deviation of about 3.3%. Obviously, the
25 step from zero to 28 Gauss resulted in overcompensation, so that a somewhat smaller magnetic field would have been ideal, while the entire exercise demonstrated the ability of the electromagnet assembly 4430 to easily handle very high chamber pressure ranges. This test was severe because at
30 higher chamber pressures the etch rate distribution tends to be more severely center low while, at the same time, the decreased collision distance or mean free path length of the higher chamber pressure makes it more difficult for a given magnetic field to effect plasma electrons or ions. This is
35 because the magnetic field can have no effect at all unless the corresponding Larmour radius of the plasma electrons or

69

ions (determined by the strength of the magnetic field and the mass of the electron or ion) does not exceed the plasma collision distance. As the collision distance decreases with increasing pressure, the magnetic field strength must
5   be increased to reduce the Larmour radius proportionately. The foregoing examples demonstrate the power of the electromagnet assembly to generate a sufficiently strong magnetic field to meet the requirement of a small Larmour radius.
10

Another set of etch processes were carried out on oxide wafers patterned with photoresist at 35 mT under similar conditions, and the current applied to the electromagnet assembly 4430 was increased in five steps from (a) 0
15   amperes, (b) 5 amperes, (c) 6 amperes, (d) 7 amperes and (e) 8 amperes. (In this test, a current of 5 amperes produces about 6 gauss measured axial magnetic field component at the wafer center.) At each step, the etch depths of high aspect ratio contact openings were measured at both the wafer
20   center and the wafer periphery to test center-to-edge etch rate uniformity control. The measured center-to-edge etch rate differences were, respectively, (a) 13.9% center low, (b) 3.3% center low, (c) 0.3% center low, (d) 2.6% center high and (e) 16.3% center high. From the foregoing, it is
25   seen that the ideal electromagnet current for best center-to-edge uniformity is readily ascertained and in this case was about 6 amperes.

A set of etch processes were carried out on blanket
30   oxide wafers to test the efficacy of the dual zone gas distribution plate 210 of FIG. 44. In a first step, the gas flow rates through the two zones were equal, in a second step the inner zone had a gas flow rate four times that of the outer zone and in a third step the outer zone had a gas
35   flow rate four times that of the inner zone. In each of these steps, no current was applied to the electromagnet

70

assembly 4430 so that the measurements taken would reflect only the effect of the dual zone gas distribution plate 210. With gas flow rates of the two zones equal in the first step, the etch rate distribution was slightly center high

5   with a standard deviation of about 2.3%. With the inner zone gas flow rate at four times that of the outer zone, the etch rate distribution was center fast with a standard deviation of about 4%. With the outer zone gas flow rate at four times that of the inner zone, the etch rate

10   distribution was center slow with a standard deviation of about 3.4%. This showed that the dual zone differential gas flow rate feature of the gas distribution plate 210 can be used to make some correction to the etch rate distribution. However, the gas flow rate control directly affects neutral

15   species distribution only, since none of the incoming gas is (or should be) ionized. On the other hand, etch rate is directly affected by plasma ion distribution and is not as strongly affected by neutral distribution, at least not directly. Therefore, the etch rate distribution control

20   afforded by the dual zone gas distribution plate, while exhibiting some effect, is necessarily less effective than the magnetic confinement of the electromagnet assembly 4430 which directly affects plasma electrons and thus ions.

25   The dependency of the electromagnet assembly 4430 upon the reentrant torroidal plasma current was explored. First a series of etch processes was carried out on blanket oxide wafers with no power applied to the torroidal plasma source, the only power being 3 kiloWatts of RF bias power applied to

30   the wafer pedestal. The electromagnet coil current was increased in four steps of (a) zero amperes, (b) 4 amperes, (c) 6 amperes and (d) 10 amperes. The etch rate distribution was observed in the foregoing steps as (a) center high with a standard deviation of 2.87%, (b) center

35   high with a standard deviation of 3.27%, (c) center high with a standard deviation of 2.93% and (d) center high with

a standard deviation of about 4%. Thus, only a small
improvement in uniformity was realized for a relatively high
D.C. current applied to the electromagnet assembly 4430.
Next, a series of etch processes was carried out under

5   similar conditions, except that 1800 Watts was applied to
each of the orthogonal tubes 150-1, 150-2. The
electromagnet coil current was increased in six steps of (a)
zero amperes, (b) 2 amperes, (c) 3 amperes, (d) 4 amperes,
(e) 5 amperes and (f) 6 amperes. The etch rate distribution

10   was, respectively, (a) center low with a standard deviation
of 1.2%, (b) center low with a standard deviation of 1.56%,
(c) center high with a standard deviation of 1.73%, (d)
center high with a standard deviation of 2.2%, (e) center
high with a standard deviation of 2.85% and (f) center high

15   with a standard deviation of 4.25%. Obviously the most
uniform distribution lies somewhere between 2 and 3 amperes
where the transition from center low to center high was
made. Far greater changes in plasma distribution were made
using much smaller coil current with much smaller changes in

20   coil current. Thus, the presence of the reentrant torroidal
plasma currents appears to enhance the effects of the
magnetic field of the electromagnet assembly 4430. Such
enhancement may extend from the increase in bias power that
is possible when the torroidal plasma source is activated.

25   In its absence, the plasma is less conductive and the plasma
sheath is much thicker, so that the bias RF power applied to
the wafer pedestal must necessarily be limited. When the
torroidal plasma source is activated (e.g., at 1800 Watts
for each of the two orthogonal tubes 150-1, 150-2) the

30   plasma is more conductive, the plasma sheath is thinner and
more bias power can be applied. As stated before herein,
the effect of the D.C. magnetic field may be dependent upon
the interaction between the D.C. magnetic field and the
electric field of the plasma sheath, which in turn depends

35   upon the RF bias power applied to the pedestal. Furthermore,
the reentrant torroidal plasma currents may be attracted to

72

the central plasma region due to the aforementioned postulated interaction between D.C. magnetic field and the electric field of the plasma sheath, further enhancing the plasma ion density in that region.

5

The effects of the port-to-port separation distance S of FIG. 55A were explored in another series of etch processes on blanket oxide wafers. The same etch process was carried out in reactors having separation distances S of
10   16.5 inches and 20.5 inches respectively. The etch rate in the one with smaller separation distance was 31% greater than in the one with the greater separation distance (i.e., 6993 vs 5332 Angstroms/minute) with 1800 Watts applied to each one of the orthogonal tubes 150-1, 150-2 with zero
15   current applied to the electromagnet assembly 4300 in each reactor.

The effects of the port-to-port separation distance S of FIGS. 55-56 were also explored in another series of etch
20   processes on oxide wafers patterned with photoresist. With 3.7 amperes applied to the electromagnet assembly 4300 having the smaller source (16.5 inch) separation distance S, the etch rate was 10450 Angstroms/minute vs 7858 Angstroms/minute using the larger source (20.5 inch)
25   separation distance S. The effect of increasing power in the reactor having the greater (20.5 inches) separation distance S was explored. Specifically, the same etch process was carried out in that reactor with source power applied to each of the orthogonal tubes 150-1, 150-2 being
30   1800 Watts and then at 2700 Watts. The etch rate increased proportionately very little, i.e., from 7858 Angstroms/minute to 8520 Angstroms/minute. Thus, the effect of the port-to-port separation distance S on plasma ion density and etch rate cannot readily be compensated by
35   changing plasma source power. This illustrates the importance of cases such as the case of FIGS. 65A, 65B and

73

66 in which a relatively short port-to-port separation distance S is accommodated while in effect lengthening the distance over which the plasma current is permitted to equilibrate after being split by the triangular splitters 5440.

The pole piece 4440 has been disclosed a being either a permanent magnet or the core of an electromagnet surrounded by a coil 4450. However, the pole piece 4440 may be eliminated, leaving only the coil 4450 as an air coil inductor that produces a magnetic field having a similar orientation to that produced by the pole piece 4440. The air coil inductor 4450 may thus replace the pole piece 4440. Therefore, in more general terms, what is required to produce the requisite radial magnetic field is an elongate pole-defining member which may be either the pole piece 4440 or an air coil inductor 4450 without the pole piece 4440 or the combination of the two. The diameter of the pole-defining member is relatively narrow to appropriately confine the peak of the radial magnetic field.

Plasma Immersion Ion Implantation:
Referring to FIG. 79, a plasma immersion ion implantation reactor in accordance with one aspect of the invention includes a vacuum chamber 8010 having a ceiling 8015 supported on an annular side wall 8020. A wafer support pedestal 8025 supports a semiconductor (e.g., silicon) wafer or workpiece 8030. A vacuum pump 8035 is coupled to a pumping annulus 8040 defined between the pedestal 8025 and the side wall 8020. A butterfly valve 8037 regulates gas flow into the intake of the pump 8035 and controls the chamber pressure. A gas supply 8045 furnishes process gas containing a dopant impurity into the chamber 8010 via a system of gas injection ports that includes the injection port 8048 shown in the drawing. For example, if

74

the wafer 8030 is a crystalline silicon wafer a portion of
which is to be implanted with a p-type conductivity dopant
impurity, then the gas supply 8045 may furnish BF_3 and/or
B_2H_6 gas into the chamber 8010, where Boron is the dopant
5   impurity species. Generally, the dopant-containing gas is a
chemical consisting of the dopant impurity, such as boron (a
p-type conductivity impurity in silicon) or phosphorus (an
n-type conductivity impurity in silicon) and a volatile
species such as fluorine and/or hydrogen. Thus, fluorides
10   and/or hydrides of boron, phosphorous or other dopant   .
species such as arsenic, antimony, etc., can be dopant
gases. In a plasma containing a fluoride and/or hydride of a
dopant gas such as BF_3, there is a distribution of various
ion species, such as BF_2+, $BF+$, $B+$, $F+$, $F-$ and others (such
15   as inert additives). All types of species may be accelerated
across the sheath and may implant into the wafer surface.
The dopant atoms (e.g., boron or phosphorous atoms)
typically dissociate from the volatile species atoms (e.g.,
fluorine or hydrogen atoms) upon impact with the wafer at
20   sufficiently high energy. Although both the dopant ions and
volatile species ions are accelerated into the wafer
surface, some portion of the volatile species atoms tend to
leave the wafer during the annealing process that follows
the ion implantation step, leaving the dopant atoms
25   implanted in the wafer.

A plasma is generated from the dopant-containing gas
within the chamber 8010 by an inductive RF power applicator
including an overhead coil antenna 8050 coupled to an RF
30   plasma source power generator 8055 through an impedance
match circuit 8060. An RF bias voltage is applied to the
wafer 8030 by an RF plasma bias power generator 8065 coupled
to the wafer support pedestal 8025 through an impedance
match circuit 8070. A radially outer coil antenna 8052 may
35   be driven independently by a second RF plasma source power
generator 8057 through an impedance match circuit 8062.

The RF bias voltage on the wafer 8030 accelerates ions from the plasma across the plasma sheath and into the wafer surface, where they are lodged in generally interstitial sites in the wafer crystal structure. The ion energy, ion mass, ion flux density and total dose may be sufficient to amorphize (damage) the structure of the wafer. The mass and kinetic energy of the dopant (e.g., boron) ions at the wafer surface and the structure of the surface itself determine the depth of the dopant ions below the wafer surface. This is controlled by the magnitude of the RF bias voltage applied to the wafer support pedestal 8025. After the ion implantation process is carried out, the wafer is subjected to an anneal process that causes the implanted dopant atoms to move into substitutional atomic sites in the wafer crystal. The substrate surface may not be crystalline if it has been pre-amorphized prior to the plasma immersion ion implant process, or if the ion energy, ion mass, ion flux density and total dose of plasma immersion ion implant process itself is sufficient to amorphize the structure of the wafer. In such a case, the anneal process causes the amorphous (damaged) layer to recrystallize with the incorporation and activation of implanted dopant. The conductance of the implanted region of the semiconductor is determined by the junction depth and the volume concentration of the activated implanted dopant species after the subsequent anneal process. If, for example, a p-type conductivity dopant such as boron is implanted into a silicon crystal which has been previously doped with an n-type dopant impurity, then a p-n junction is formed along the boundaries of the newly implanted p-type conductivity region, the depth of the p-n junction being the activated implanted depth of the p-type dopant impurities after anneal. The junction depth is determined by the bias voltage on the wafer (and by the anneal process), which is controlled by the power level of the RF plasma bias power

76

generator 8065. The dopant concentration in the implanted
region is determined by the dopant ion flux ("dose") at the
wafer surface during implantation and the duration of the
ion flux. The dopant ion flux is determined by the
5   magnitude of the RF power radiated by the inductive RF power
applicator 8050, which is controlled by the RF plasma source
power generator 8055. This arrangement enables independent
control of the time of implant, the conductivity of the
implanted region and the junction depth. Generally, the
10   control parameters such as the power output levels of the
bias power RF generator 8065 and the source power RF
generator 8055 are chosen to minimize the implant time while
meeting the target values for conductivity and junction
depth. For more direct control of ion energy, the bias
15   generator may have "voltage" rather than "power" as its
output control variable.

An advantage of the inductive RF plasma source power
applicator 8050 is that the ion flux (the dopant dose rate)
20   can be increased by increasing the power level of the RF
source power generator 8055 without a concomitant increase
in plasma potential. The bias voltage level is controlled
by the RF bias power generator at a preselected value
(selected for the desired implant depth) while the inductive
25   RF source power is increased to increase the ion flux (the
dopant dose rate) without significantly increasing the
plasma potential. This feature minimizes contamination due
to sputtering or etching of chamber surfaces. It further
reduces the consumption of consumable components within the
30   chamber that wear out over time due to plasma sputtering.
Since the plasma potential is not necessarily increased with
ion flux, the minimum implant energy is not limited
(increased), thereby allowing the user to select a shallower
junction depth than would otherwise have been possible. In
35   contrast, it will be recalled that the microwave ECR plasma
source was characterized by a relatively high minimum plasma

77

potential, which therefore limited the minimum implant energy and therefore limited the minimum junction depth.

An advantage of applying an RF bias voltage to the wafer (instead of a D.C. bias voltage) is that it is far more efficient (and therefore more productive) for ion implantation, provided the RF bias frequency is suitably chosen. This is illustrated in FIGS. 80A, 80B and 80C. FIG. 80A illustrates a one-millisecond D.C. pulse applied to the wafer in conventional practice, while FIG. 80B illustrates the resulting ion energy at the wafer surface. The D.C. pulse voltage of FIG. 80A is near the target bias voltage at which ions become substitutional upon annealing at the desired implant junction depth. FIG. 80B shows how the ion energy decays from the initial value corresponding to the voltage of the pulse of FIG. 80A, due to resistive-capacitive effects at the wafer surface. As a result, only about the first micro-second (or less) of the one-millisecond D.C. pulse of FIG. 80A is actually useful, because it is only this micro-second portion of the pulse that produces ion energies capable of implanting ions that become substitutional (during annealing) at the desired junction depth. The initial (one microsecond) period of the D.C. pulse may be referred to as the RC time. During the remaining portion of the D.C. pulse, ions fail to attain sufficient energy to reach the desired depth or to become substitutional upon annealing, and may fail to penetrate the wafer surface so as to accumulate in a deposited film that resists further implantation. This problem cannot be solved by increasing the pulse voltage, since this would produce a large number of ions that would be implanted deeper than the desired junction depth. Thus, ions are implanted down to the desired junction depth during only about a tenth of a percent of the time. This increases the time required to reach the target implant density at the desired junction depth. The resulting spread in energy also reduces the

78

abruptness of the junction.   In contrast, each RF cycle in
a 1 millisecond burst of a 1 MHz RF bias voltage illustrated
in FIG. 80C has an RF cycle time not exceeding the so-called
RC time of FIG. 80B.   As a result, resistive-capacitive

5   effects encountered with a pulsed D.C. bias voltage are
generally avoided with an RF bias voltage of a sufficient
frequency.   Therefore, ions are implanted down to the
desired junction depth during a far greater percentage of
the time of the 1 MHz RF bias voltage of FIG. 80C.   This

10   reduces the amount of time required to reach a target
implant density at the desired junction depth.   Thus, the
use of an RF bias voltage on the wafer results in far
greater efficiency and productivity than a D.C. pulse
voltage, depending upon the choice of RF frequency.

15

    The frequency of the RF bias is chosen to satisfy the
following criteria: The RF bias frequency must be
sufficiently high to have a negligible voltage drop across
the pedestal (cathode) dielectric layers) and minimize

20   sensitivity to dielectric films on the backside or front
side of the wafer and minimize sensitivity to chamber wall
surface conditions or deposition of plasma by-products.
Moreover, the frequency must be sufficiently high to have a
cycle time not significantly exceeding the initial period

25   (e.g., one micro-second) before resistive-capacitive (RC)
effects reduce ion energy more than 2% below the target
energy, as discussed immediately above.   Furthermore, the RF
bias frequency must be sufficiently high to couple across
insulating capacitances such as films on the wafer surface,

30   dielectric layers on the wafer support pedestal, coatings on
the chamber walls, or deposited films on the chamber walls.
(An advantage of RF coupling of the bias voltage to the
wafer is that such coupling does not rely upon ohmic contact
and is less affected by changes or variations in the surface

35   conditions existing between the wafer and the support
pedestal.)   However, the RF bias frequency should be

79

sufficiently low so as to not generate significant plasma sheath oscillations (leaving that task to the plasma source power applicator). More importantly, the RF bias frequency should be sufficiently low for the ions to respond to the oscillations of the electric field in the plasma sheath overlying the wafer surface. The considerations underlying this last requirement are now discussed with reference to FIGS. 81A through 81D.

FIG. 81A illustrates the plasma ion saturation current at the wafer surface as a function of D.C. bias voltage applied to the wafer, the current being greatest (skewed toward) the higher voltage region. FIG. 81B illustrates the oscillation of the RF voltage of FIG. 80C. The asymmetry of the ion saturation current illustrated in FIG. 80A causes the ion energy distribution created by the RF bias voltage of FIG. 80B to be skewed in like manner toward the higher energy region, as illustrated in FIG. 80C. The ion energy distribution is concentrated most around an energy corresponding to the peak-to-peak voltage of the RF bias on the wafer. But this is true only if the RF bias frequency is sufficiently low for ions to follow the oscillations of the electric field in the plasma sheath. This frequency is generally a low frequency around 100 kHz to 3 MHz, but depends on sheath thickness and charge-to-mass ratio of the ion. Sheath thickness is a function of plasma electron density at the sheath edge and sheath voltage. Referring to FIG. 81D, as this frequency is increased from the low frequency (denoted F1 in FIG. 81D) to a medium frequency (denoted F2 in FIG. 81D) and finally to a high frequency such as 13 MHz (denoted F3 in FIG. 81D), the ability of the ions to follow the plasma sheath electric field oscillation is diminished, so that the energy distribution is narrower. At the HF frequency (F3) of FIG. 81D, the ions do not follow the sheath electric field oscillations, and instead achieve an energy corresponding to the average voltage of

80

the RF bias voltage, i.e., about half the RF bias peak-to-peak voltage. As a result, the ion energy is cut in half as the RF bias frequency increases to an HF frequency (for a constant RF bias voltage). Furthermore, at the medium

5   frequency, we have found that the plasma behavior is unstable in that it changes sporadically between the low frequency behavior (at which the ions have an energy corresponding to the peak-to-peak RF bias voltage) and the high frequency behavior (at which the ions have an energy

10   corresponding to about half the peak-to-peak RF bias voltage). Therefore, by maintaining the RF bias frequency at a frequency that is sufficiently low (corresponding to the frequency F1 of FIG. 81D) for the ions to follow the plasma sheath electric field oscillations, the RF bias peak-

15   to-peak voltage required to meet a particular ion implant depth requirement is reduced by a factor of nearly two, relative to behavior at a medium frequency (F2) or a high frequency (F3). This is a significant advantage because such a reduction in the required RF bias voltage (e.g., by a

20   factor of two) greatly reduces the risk of high voltage arcing in the wafer support pedestal and the risk of damaging thin film structures on the wafer. This is particularly important because in at least a particular plasma immersion ion implantation source described later in

25   this specification, ion energies match those obtained in a conventional ion beam implanter, provided the plasma RF bias voltage is twice the acceleration voltage of the conventional ion beam implanter. Thus, at a high frequency plasma RF bias voltage, where ion energies tend to be half

30   those obtained at low frequency, the required plasma RF bias voltage is four times the acceleration voltage of the conventional ion beam implanter for a given ion energy level. Therefore, it is important in a plasma immersion ion implantation reactor to exploit the advantages of a low

35   frequency RF bias voltage, to avoid the necessity of excessive RF bias voltages.

Good results are therefore attained by restricting the
RF bias power frequency to a low frequency range between 10
kHz and 10 MHz. Better results are obtained by limiting the
RF bias power frequency to a narrower range of 50 kHz to 5
MHz. The best results are obtained in the even narrower
bias power frequency range of 100 kHz to 3 MHz. We have
found optimum results at about 2 MHz plus or minus 5%.

Both the RF source power generator 8055 and the RF bias
power generator 8065 may apply continuous RF power to the
inductive power applicator 8050 and the wafer pedestal 8025
respectively. However, either or both of the generators
8055, 8065 may be operated in burst modes controlled by a
controller 8075. The controller 8075 may also control the
generator 8057 in a burst mode as well if the outer coil
antenna 8052 is present. Operation in an implementation not
including the outer coil antenna 8057 will now be described.
The RF signals produced by each of the generators 8055, 8065
may be pulse modulated to produce continuous wave (CW) RF
power in bursts lasting, for example, one millisecond with a
repetition rate on the order of 0.5 kHz, for example.
Either one or both of the RF power generators 8055, 8065 may
be operated in this manner. If both are operated in such a
burst mode simultaneously, then they may be operated in a
push-pull mode, or in an in-synchronism mode, or in a
symmetrical mode or in a non-symmetrical mode, as will now
be described.

A push-pull mode is illustrated in the contemporaneous
time domain waveforms of FIGS. 82A and 82B, illustrating the
RF power waveforms of the respective RF generators 8055 and
8065, in which the bursts of RF energy from the two
generators 8055, 8065 occur during alternate time windows.
FIGS. 82A and 82B illustrate the RF power waveforms of the
generators 8055 and 8065, respectively, or vice versa.

82

An in-synchronism mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82C and 82D, in which the bursts of RF energy from the two generators

5   8055, 8065 are simultaneous. They may not be necessarily in phase, however, particularly where the two generators 8055, 8065 produce different RF frequencies. For example, the RF plasma source power generator 8055 may have a frequency of about 13 MHz while the RF plasma bias power generator 8065

10   may have a frequency of about 2 MHz. FIGS. 82C and 82D illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

In the foregoing examples, the pulse widths and pulse

15   repetition rates of the two RF generators 8055, 8065 may be at least nearly the same. However, if they are different, then the temporal relationship between the bursts of the two generators 8055, 8065 must be selected. In the example of the contemporaneous time domain waveforms of FIGS. 82E and

20   82F, one of the generators 8055, 8065 produces shorter RF bursts illustrated in FIG. 82F while the other produces longer RF bursts illustrated in FIG. 82E. In this example, the bursts of the two generators 8055, 8065 are symmetrically arranged, with the shorter bursts of FIG. 82F

25   centered with respect to the corresponding longer bursts of FIG. 82E. FIGS. 82E and 82F illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

30   In another example, illustrated in the contemporaneous time domain waveforms of FIGS. 82G and 82H, the shorter bursts (FIG. 82H) are not centered relative to the corresponding longer bursts (FIG. 82G), so that they are asymmetrically arranged. Specifically, in this example the

35   shorter RF bursts of FIG. 82H coincide with the later portions of corresponding ones of the long bursts of FIG.

83

82G. Alternatively, as indicated in dashed line in FIG.
82H, the short RF bursts of FIG. 82H may instead coincide
with the earlier portions of corresponding ones of the long
RF bursts of FIG. 82G. FIGS. 82G and 82H illustrate the RF
5   power waveforms of the generators 8055 and 8065,
respectively, or vice versa.

The inductive RF source power applicator 8050 of FIG.
79 tends to exhibit a rapid increase in dissociation of
10   fluorine-containing species in the plasma as plasma source
power (and ion flux) is increased, causing undue etching of
semiconductor films on the wafer during the implantation
process. Such etching is undesirable. A plasma immersion
ion implantation reactor that tends to avoid this problem is
15   illustrated in FIG. 83A. The plasma immersion ion
implantation reactor of FIG. 83A has a capacitive source
power applicator constituting a conductive (metal) or
semiconducting ceiling 8015' electrically insulated from the
grounded side wall 8020 by an insulating ring 8017.
20   Alternatively, the ceiling may be metal, conductive, or
semiconducting and be coating by an insulating, conducting
or semiconducting layer. The RF plasma source power
generator 8055 drives the ceiling 8015' through the
impedance match circuit 8060 in the manner of a capacitive
25   plate. Plasma is generated by oscillations in the plasma
sheath produced by the RF power capacitively coupled from
the ceiling 8015'. In order to enhance such plasma
generation, the frequency of the plasma RF source power
generator 8055 is relatively high, for example within the
30   very high frequency (VHF) range or **30** MHz and above. The
wafer pedestal 8025 may serve as a counter electrode to the
ceiling 8015'. The ceiling 8015' may serve as a counter
electrode to the RF bias voltage applied to the wafer
pedestal 8025. Alternatively, the chamber wall may serve as
35   a counter electrode to either or both wafer bias and ceiling

84

bias voltages. In one implementation, the dopant-containing gas is fed through the ceiling 8015' through plural gas injection orifices 8048'.

5   The capacitively coupled plasma ion immersion implantation reactor of FIG. 83A enjoys the advantages of the inductively coupled reactor of FIG. 79 in that both types of reactors permit the independent adjustment of ion flux (by adjusting power level of the plasma source power
10   generator 8055) and of the ion energy or implant depth (by adjusting the power level of the plasma bias power generator 8065). In addition, when plasma source power or ion flux is increased, the capacitively coupled plasma ion immersion reactor of FIG. 83A exhibits a smaller increase in
15   dissociation of fluorine-containing species in the gas fed from the dopant gas supply 8045 and a smaller increase in reaction by-products which would otherwise lead to excessive etch or deposition problems. The advantage is that ion flux may be increased more freely without causing an unacceptable
20   level of etching or deposition during ion implantation.

       The higher frequency RF power of the plasma source power generator 8055 controls plasma density and therefore ion flux at the wafer surface, but does not greatly affect
25   sheath voltage or ion energy. The lower frequency RF power of the bias power generator 8065 controls the sheath voltage and therefore the ion implantation energy and (junction) depth and does not contribute greatly to ion generation or ion flux. The higher the frequency of the plasma source
30   power generator, the less source power is wasted in heating ions in the plasma sheath, so that more of the power is used to generate plasma ions through oscillations of the plasma sheath or by heating electrons in the bulk plasma. The lower frequency of the RF bias power generator 8065 is less
35   than 10 MHz while the higher frequency of the RF plasma source power generator 8055 is greater than 10 MHz. More

preferably, the lower frequency is less than 5 MHz while the higher frequency is greater than 15 MHz. Even better results are obtained with the lower frequency being less than 3 MHz and the higher frequency exceeding 30 MHz or even

5   50 MHz. In some cases the source power frequency may be as high as 160 MHz or over 200 MHz. The greater the separation in frequency between the higher and lower frequencies of the source and bias power generators 8055, 8065, respectively, the more the plasma ion implant flux and the plasma ion

10   implant energy can be separately controlled by the two generators 8055, 8065.

In the variation illustrated in FIG. 83B, the RF plasma source power generator 8055 is coupled to the wafer pedestal

15   rather than being coupled to the ceiling 8015'. An advantage of this feature is that the ceiling 8015' is consumed (by plasma sputtering or etching) at a much lower rate than in the reactor of FIG. 83A, resulting in less wear and less metallic contamination of the plasma. A

20   disadvantage is that isolation between the two RF generators 8055, 8065 from each other is inferior compared to the reactor of FIG. 83A, as they are both connected to the same electrode, so that control of ion flux and ion energy is not as independent as in the reactor of FIG. 83A.

25

In either of the reactors of FIGS. 83A or 83B, the controller 8075 can operate in the manner described above with reference to FIGS. 82A through 82H, in which the respective RF power waveforms applied to the ceiling 8015'

30   and the pedestal 8025 are in a push-pull mode (FIGS. 82A and B), or an in-synchronism mode (FIGS. 82C and D), or a symmetric mode (FIGS. 802E and F) or a non-symmetric mode (FIGS. 82G and H).

35   FIGS. 83A and 83B show that the RF source power generator 8055 can drive the ceiling 8015' (FIG. 83A) with

the side wall 8020 and/or the wafer support pedestal 8025
connected to the RF return terminal of the generator 8055,
or, in the alternative, the RF source power generator 8055
can drive the wafer support pedestal 8025 with the ceiling

5   8015' and/or the sidewall 8020 connected to the RF return
terminal of the generator 8055. Thus, the RF source power
generator is connected across the wafer support pedestal
8025 and the sidewall 8020 or the ceiling 8015' (or both).
The polarity of the connections to the source power

10   generator 8055 may be reversed, so that it drives the side
wall 8020 and/or ceiling 8015' with the pedestal 8025 being
connected to the RF return terminal of the generator 8055.

As set forth above, the plasma immersion ion

15   implantation inductively coupled reactor of FIG. 79 has
distinct advantages, including (a) the capability of a large
ion flux/high plasma ion density, (b) independently
controlled ion energy, and (c) low minimum ion energy
(plasma potential). The plasma immersion ion implantation

20   capacitively coupled reactor of FIG. 83A has the additional
advantage of having more controllable dissociation of
process gases and reactive byproducts as ion flux is
increased, than the inductively coupled reactor of FIG. 79.
However, the capacitively coupled reactor of FIG. 83A has a

25   higher minimum ion energy/plasma potential than the
inductively coupled reactor of FIG. 79. Thus, these two
types of reactors provide distinct advantages, but neither
provides all of the advantages.

30   A plasma immersion ion implantation reactor that
provides all of the foregoing advantages, including low
minimum ion energy and low process gas dissociation, is
illustrated in FIG. 84. In FIG. 84, the inductively or
capacitively coupled plasma sources of FIG. 79 or 83A are

35   replaced by a torroidal plasma source of the type disclosed
above in FIGS. 1-78. In the basic configuration of FIG. 84,

87

the torroidal plasma source includes a reentrant hollow
conduit 8150 over the ceiling 8015, corresponding to the
conduit 150 of FIG. 1. The conduit 8150 of FIG. 84 has one
open end 8150a sealed around a first opening 8155 in the
ceiling 8015 and an opposite open end 8150b sealed around a
second opening 8160 in the ceiling 8015. The two openings
or ports 8155, 8160 are located in the ceiling over opposite
sides of the wafer support pedestal 8025. While FIG. 84
illustrates the openings 8155, 8160 being in the ceiling,
the openings could instead be in the base or floor of the
chamber, as in FIG. 12, or in the side wall of the chamber,
as in FIG. 26, so that the conduit 8150 may pass over or
under the chamber. RF plasma source power is coupled from
the RF generator 8055 through the optional impedance match
circuit 8060 to the reentrant conduit by an RF plasma source
power applicator 8110. Various types of source power
applicators for a reentrant hollow conduit are disclosed in
FIGS. 1-78, any one of which may be employed in the plasma
immersion ion implantation reactor of FIG. 84. In the
implementation illustrated in FIG. 84, the RF plasma source
power applicator 8110 is similar to that illustrated in FIG.
13, in which a magnetically permeable core 8115 having a
torus shape surrounds an annular portion of the conduit
8150. The RF generator 8055 is coupled through the optional
impedance match circuit to a conductive winding 8120 around
the magnetic core 8115. An optional tuning capacitor 8122
may be connected across the winding 8120. The RF generator
8055 may be frequency-tuned to maintain an impedance match,
so that the impedance match circuit 8060 may not be
necessary.

The reactor chamber includes the process region 8140
between the wafer support pedestal 8025 and the ceiling
8015. The gas supply 8045 furnishes dopant gases into the
reactor chamber 8140 through gas injection orifices 8048 in
the ceiling 8015. Plasma circulates (oscillates) through

88

the reentrant conduit 8150 and across the process region 8140 in response to the RF source power coupled by the source power applicator 8110. As in the reactor of FIG. 13, the reentrant conduit 8150 is formed of a conductive

5   material and has a narrow gap or annular break 8152 filled with an insulator 8154. The dopant gases furnished by the gas supply 8045 contain a species that is either a donor (N-type) or acceptor (P-type) impurity when substituted into the semiconductor crystal structure of the wafer 8030. For

10   example, if the wafer is a silicon crystal, then an N-type dopant impurity may be arsenic or phosphorous, for example, while a P-type dopant impurity may be boron, for example. The dopant gas furnished by the gas supply 8045 is a chemical combination of the dopant impurity with an at-least

15   partially volatile species, such as fluorine for example. For example, if a P-type conductivity region is to be formed by ion implantation, then the dopant gas may be a combination of boron and fluorine, such as BF_3, for example. Or, for example, the dopant gas be a hydride, such as B_2H_6.

20   Phosphorous doping may be accomplished using a fluoride such as PF_3 or PF_5 or a hydride such as PH_3. Arsenic doping may be accomplished using a fluoride such as AsF_5 or a hydride such as AsH_3.

25   The RF bias power generator provides an RF bias voltage, with the RF bias frequency selected as described above with reference to FIG. 81D. Good results are attained by restricting the RF bias power frequency to a low frequency range between 10 kHz and 10 MHz. Better results

30   are obtained by limiting the RF bias power frequency to a narrower range of 50 kHz to 5 MHz. The best results are obtained in the even narrower bias power frequency range of 100 kHz to 3 MHz. We have found optimum results at about 2 MHz plus or minus 5%.

35

        In the reactor of FIG. 84, both the RF source power

89

generator 8055 and the RF bias power generator 8065 may apply continuous RF power to the inductive power applicator 8110 and the wafer pedestal 8025 respectively. However, either or both of the generators 8055, 8065 may be operated
5   in burst modes controlled by a controller 8075. The RF signals produced by each of the generators 8055, 8065 may be pulse modulated to produce continuous wave (CW) RF power in bursts lasting, for example, one millisecond with a repetition rate on the order of 0.5 kHz, for example.
10 Either one or both of the RF power generators 8055, 8065 may be operated in this manner. If both are operated in such a burst mode simultaneously, then they may be operated in a push-pull mode, or in an in-synchronism mode, or in a symmetrical mode or in a non-symmetrical mode, as will now
15 be described for the reactor of FIG. 84.

A push-pull mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82A and 82B, illustrating the RF power waveforms of the respective RF generators 8055 and
20 8065, in which the bursts of RF energy from the two generators 8055, 8065 occur during alternate time windows. FIGS. 82A and 82B illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

25   An in-synchronism mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82C and 82D, in which the bursts of RF energy from the two generators 8055, 8065 are simultaneous. They may not be necessarily in phase, however, particularly where the two generators 8055,
30 8065 produce different RF frequencies. For example, the RF plasma source power generator 8055 may have a frequency of about 13 MHz while the RF plasma bias power generator 8065 may have a frequency of about 2 MHz. FIGS. 82C and 82D illustrate the RF power waveforms of the generators 8055 and
35 8065, respectively, or vice versa.

In the foregoing examples, the pulse widths and pulse repetition rates of the two RF generators 8055, 8065 may be at least nearly the same. However, if they are different, then the temporal relationship between the bursts of the two generators 8055, 8065 must be selected. In the example of the contemporaneous time domain waveforms of FIGS. 82E and 82F, one of the generators 8055, 8065 produces shorter RF bursts illustrated in FIG. 82F while the other produces longer RF bursts illustrated in FIG. 82E. In this example, the bursts of the two generators 8055, 8065 are symmetrically arranged, with the shorter bursts of FIG. 82F centered with respect to the corresponding longer bursts of FIG. 82E. FIGS. 82E and 82F illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

In another example, illustrated in the contemporaneous time domain waveforms of FIGS. 82G and 82H, the shorter bursts (FIG. 82H) are not centered relative to the corresponding longer bursts (FIG. 82G), so that they are asymmetrically arranged. Specifically, in this example the shorter RF bursts of FIG. 82H coincide with the later portions of corresponding ones of the long bursts of FIG. 82G. Alternatively, as indicated in dashed line in FIG. 82H, the short RF bursts of FIG. 82H may instead coincide with the earlier portions of corresponding ones of the long RF bursts of FIG. 82G. FIGS. 82G and 82H illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

The torroidal plasma immersion ion implantation reactor of FIG. 84 can be operated with a pulsed D.C. bias voltage instead of an RF bias voltage. In this case, the bias power generator 8065 would be D.C. source rather than an RF source. Thus, in the different operational modes of FIGS. 82A through 82H discussed above, the pulsed RF bias voltage

91

may be replaced by a pulsed D.C. bias voltage of the same
pulse width, with only the source power generator 8055
producing an RF power burst.

5   FIG. 85 illustrates a modification of the plasma
immersion ion implantation reactor of FIG. 84 having a
second reentrant conduit 8151 crossing the first reentrant
conduit 8150, in a manner similar to the reactor of FIG. 44.
Plasma power is coupled to the second conduit 8151 from a
10   second RF plasma source power generator 8056 through a
second optional match circuit 8061 to a second source power
applicator 8111 that includes a second magnetically
permeable core 8116 and a second core winding 8121 driven by
the second RF source power generator 8056. Process gas from
15   the gas supply 8045 may be introduced into the chamber by a
gas distribution plate or showerhead incorporated in the
ceiling 8015 (as in the gas distribution plate 210 of FIG.
44). However, the plasma immersion ion implantation reactor
of FIG. 85 is greatly simplified by using a small number of
20   process gas injectors 8048 in the ceiling 8015 or in the
side wall 8020 or elsewhere, such as in the base of the
chamber (not shown) coupled to the dopant gas supply, rather
than a showerhead. Moreover, the gap between the ceiling
8015 and the wafer pedestal 8025 may be relatively large
25   (e.g., two to six inches) and a gas distribution plate
eliminated in favor of discrete gas injectors or diffuser
8048 in the ceiling 8015 or gas injectors or diffusers 8049
in the side wall 8020 because there is no need to generate
plasma close to the wafer surface. The gas injectors or
30   diffusers 8049 may be joined in a ring 8049 on the side wall
8020. Generally, the higher the maximum implant depth and
ion energy requirement, the greater the gap between ceiling
and wafer that is required. For example, for a peak-to-peak
RF bias voltage of 10 kV, a gap of 4 inches is preferable
35   over a 2 inch gap for best plasma uniformity across a wide
range of gas species and plasma electron densities. The

92

term diffuser is employed in the conventional sense as referring to a type of gas distribution device having a wide angle of gas flow distribution emanating from the device.

5   FIG. 86 is a plan view of the interior surface of the ceiling 8015, showing one arrangement of the gas injection orifices 8048, in which there is one central orifice 8048-1 in the center of the ceiling 8015 and four radially outer orifices 8048-2 through 8048-5 uniformly spaced at an outer
10   radius. FIG. 87 illustrates how the dopant gas supply 8045 may be implemented as a gas distribution panel. The gas distribution panel or supply 8045 of FIG. 87 has separate gas reservoirs 8210-1 through 8210-11 containing different dopant-containing gases including fluorides of boron,
15   hydrides of boron, fluorides of phosphorous and hydrides of phosphorous. In addition, there are gas reservoirs for other gases used in co-implantation (hydrogen and helium), material enhancement (nitrogen), surface passivation or co-implantation (fluorides of silicon or germanium or carbon).
20   In addition, the center orifice 8048-1 may be coupled to a reservoir oxygen gas, for use in photoresist removal and/or chamber cleaning. A control panel 8220 includes valves 8222 controlling gas flow from the respective reservoirs 8210 to the gas injection orifices. Preferably, the gases are mixed
25   at or near the orifices, although a gas manifold 8230 may be provided to distribute the selected gases among the outer gas injection orifices 8048-2 through 8048-5. Alternatively, process gas may be injected at one or more locations in the sidewall 8020, using the nozzles 8049 of FIG. 85 or
30   diffusers. Figure 85 shows gas injectors 8049 located around the chamber sidewalls 8020 which inject gas radially inward. Gas may be injected parallel to the ceiling and/or wafer, or may be injected with some component toward ceiling and/or wafer. For some applications, it is advantageous to utilize
35   multiple separate gas plenums, each with its own nozzle array. This can permit the use of chemistries which should

not be combined except under vacuum, or may permit having several gas zones for neutral uniformity tuning. For this purpose, referring again to FIG. 85, a first ring 8049a joining a first set of side wall injectors 8049c serves as a first plenum, while a second ring 8049b joining a second separate set of side wall injectors 8049d serves as a second plenum. The two rings or plenums 8049a, 8049b are supplied by separate respective sets of valves 8222 of the gas panel of FIG. 87

FIG. 88 illustrates a modification of the plasma immersion ion implantation reactor of FIG. 85 in which a central electromagnet assembly 8430 is mounted over the center of the ceiling 8015. Like the electromagnet assembly 4430 of FIG. 44, the electromagnet assembly 8430 of FIG. 88 controls plasma ion density uniformity and includes a narrow elongate cylindrical pole piece 8440 formed of a magnetizable material such as iron or steel and a coil 8450 of insulated conductive wire wrapped around the pole piece 8440. A magnetic current controller 8442 supplies an electrical current to the coil 8450. The controller 8442 controls the current through the coil 8450 so as to optimize uniformity of plasma ion density (ion flux) across the wafer surface.

FIGS. 89A and 89B are side and top views, respectively, illustrating a further modification incorporating a radially outer electromagnet assembly 8460. The outer electromagnet assembly 8460 is in the shape of a torus and overlies an annular outer region of the ceiling 8015 near the circumferential edge of the ceiling 8015 and adjacent the ports pairs 150, 160 of the conduits 8150, 8151. Referring to the cross-sectional view of FIG. 90A, the outer electromagnet assembly 8460 includes a coil 8462 consisting of plural windings of a single conductor connected to the current controller 8442. In order to concentrate the

94

magnetic field of the outer electromagnet assembly 8460
within the process region 8140, an overlying magnetic cover
8464 surrounding the sides and top of the coil 8462 but not
the bottom of the coil 8462. The magnetic cover 8464
5   permits the magnetic field of the coil 8462 to extend
downwardly below the ceiling into the process region 8140.
Uniformity of the ion density and radial plasma flux
distribution at the wafer surface is optimized by
independently adjusting the currents in the inner and outer
10   electromagnet assemblies 8430, 8460.

In order to avoid forming regions of very high plasma
ion concentration near the ports 150, 160 of the two
conduits 8150, 8151, individual plates 8466 of magnetically
15   permeable material (e.g., iron or steel) are placed under
the outer electromagnet assembly 8460 adjacent respective
ones of the ports 150, 160. The circumferential extent of
each plate 8466 is approximately equal to the width of each
individual port 150, 160. FIGS. 90A, 90B and 90C are cross-
20   sectional views taken along lines 90-90 of FIG. 89B. The
distance between the plate 8466 and the bottom edge of the
magnetic cover 8464 may be adjusted to control the amount of
magnetic field coupled into portion of the process region
near each individual one of the ports 150, 160. In FIG.
25   90A, the plate 8466 is in contact with the bottom edges of
the cover 8464, so that the magnetic field near the
corresponding port (150, 160) is almost completely confined
within the enclosure defined by the cover 8464 and the plate
8466. In FIG. 90B, the plate 8466 is slightly displaced
30   from the bottom edge of the cover 8464, creating a small gap
therebetween that allows a small magnetic field to enter the
process region 8140 near the corresponding port (150, 160).
In FIG. 90C, there is a large gap between the plate 8466 and
the cover 8464, permitting a larger magnetic field to exist
35   in the process region near the corresponding port (150,
160).

FIG. 91 illustrates how the RF plasma bias power
generator 8065 may be coupled to the wafer support pedestal
8025. An inductor 8510 and a variable capacitor 8520 are
connected in parallel between one side of a series capacitor
8530 and ground, the other side of the series capacitor 8530
being connected to the wafer support pedestal 8025. The
output of the bias power generator 8065 is connected to a
tap 8560 of the inductor 8510. The position of the tap 8560
and the capacitance of the variable capacitor 8520 are
selected to provide an impedance match between the bias
power generator 8065 and the plasma load at the wafer
pedestal 8065. The variable capacitor 8520 may be controlled
by a system controller 8525 to optimize matching. In this
case, the circuit including the parallel inductor and
capacitor 8510, 8520 serves as an impedance match circuit.

In order to follow variations in the plasma load impedance
during processing, frequency tuning of the bias power
generator 8065 may be employed, although this may not be
necessary. The position of the tap 8560 may be selectable
either manually or by the system controller 8525 to optimize
matching. Alternatively, a capacitor (not shown) may be
connected between the tap position and ground or between RF
bias generator and tap point as an alternative matching
circuit topology. This optional capacitor may be controlled
by the system controller 8525 to optimize matching.

One problem in selecting the bias voltage level is that
large ion energy can be reached only with a high bias
voltage level, which typically requires high power. High
power contributes to the plasma flux (ion density or dose
rate), and can cause too high a dose rate, making it
difficult to control the conductivity of the implanted
region. One way of controlling the dose rate at such a high
power is to pulse the RF bias power. However, controlling
the pulse rate and pulse width of repetitive pulses so as to

96

achieve the required dose rate and conductivity is
difficult. Part of the problem is that ion implantation at
the desired junction depth is achieved only after the bias
voltage has risen sufficiently (at the beginning of a pulse
5   or RF burst) to reach a threshold voltage corresponding to
the desired junction depth and ion energy. The solution to
this problem is to avoid repetitive pulsing of the bias
power, and instead use a single pulse of sufficient duration
to complete ion implantation at the desired junction depth
10   and conductivity in the implanted region. This is
illustrated in the time domain waveform of FIG. 92. A timer
can be employed to guarantee that the RF burst or pulse
lasts the required duration (Ttimer). However, the timer
must not begin until the sheath voltage has reached the
15   threshold voltage (Vthreshold) at which ion implantation
occurs at the required depth. Thus, FIG. 92 shows that the
sheath voltage grows at the beginning of bias power RF burst
(Ton) until it reaches Vthreshold after several cycles. At
that point, the timer begins, and ends the RF burst at the
20   expiration of Ttimer, i.e., at Toff. The problem,
therefore, is how to ascertain the time at which the sheath
voltage reaches Vthreshold, i.e., when to begin Ttimer.

Another problem is how to ascertain the requisite power
25   level of the bias power generator 8065 at which Vthreshold
is produced across the sheath.

FIG. 93 illustrates a control circuit for determining
the bias generator power level that produces the desired
30   sheath voltage and for determining when the target sheath
voltage has been reached for beginning the RF burst timer.
In the following description, the target bias voltage
corresponding to a desired junction depth, has already been
determined. In addition, the threshold voltage for
35   implantation has also been determined, and the threshold
voltage may be synonymous with the target bias voltage.

97

Finally, the duration time for applying RF bias power at the target bias voltage has already been determined. The RF bias power generator 8065 is controlled by a timer 8670 that begins counting sometime after the beginning of an RF burst and times out after a predetermined duration. A threshold comparator 8672 compares the peak-to-peak voltage as detected at the wafer pedestal 8025 by a peak detector 8674 with the desired threshold voltage 8676. The timer 8670 is enabled only when it receives an affirmative signal from an optical detector 8678 indicating that plasma is ignited within the reactor chamber. If the optical detector 8678 sends an affirmative signal, then the timer 8670 begins counting as soon as the comparator 8672 determines that the peak-to-peak bias voltage has reached the desired threshold. When the timer 8670 times out (after the predetermined duration), it turns off the output of the bias power generator, thus terminating the current burst of RF bias power. The timer 8670 and the threshold comparator 8672 constitute a timer control loop 8680.

The power level of the bias power generator 8065 is controlled by a voltage control loop 8682. A process controller 8684 (or the process designer) determines the desired or "target" bias peak-to-peak voltage. This may be synonymous with the threshold voltage of 8676. A subtractor 8686 computes an error value as the difference between the actual peak bias voltage measured by the detector 8674 and the target bias voltage. A proportional integral conditioner 8688 multiplies this error value by a constant of proportionality, k, and integrates the error value with prior samples. The result is an estimated correction to the power level of the bias power generator 8065 that will bring the measured bias voltage closer to the target bias voltage. This estimate is superimposed on the current power level, and the result is an estimated power level command that is applied to the power set input of the bias power generator

98

8065. This estimate is only valid while plasma is ignited (i.e., during an RF burst). For times between RF bursts, the bias power level is controlled in accordance with a look-up table 8690 that correlates target peak-to-peak bias

5 voltages with estimated bias power levels. The look-up table receives the target bias voltage from the process controller 8684 and in response outputs an estimated bias power level. A pair of switches 8694, 8696 are enabled in complementary fashion by the output of the plasma ignition

10 optical detector 8678. Thus, the switch 8694 receives the output of the sensor 8678 while the switch 8696 receives the inverted output of the sensor 8678. Thus, during an RF burst, when plasma is ignited in the chamber, the output of the proportional integral conditioner 8688 is applied to the

15 power set input of the bias generator 8065 via the switch 8694. Between RF bursts, or when no plasma is ignited in the chamber, the output of the look-up table 8690 is applied via the switch 8696 to the power set input of the bias power generator 8065. The output of the look up table 8690 may be

20 considered as a gross estimate that serves to initialize the RF bias power level at the beginning of each RF burst, while the output of the integral proportional conditioner is a more accurate estimate based upon actual measurement that serves to correct the bias power level during the RF burst.

25

One problem in the plasma immersion ion implantation reactor of FIG. 89A is that most ion implantation processes must be carried out with precise fine control over chamber pressure. This requires a relatively gradual change in

30 chamber pressure over a given rotation of the control valve 8037 from its closed position. On the other hand, some processes, including chamber cleaning, require a very high gas flow rate (e.g., of cleaning gases) and a concomitantly high evacuation rate by the pump 8035. This requires that

35 the vacuum control valve 8037 have a large area. The problem is that with such a large area, a vacuum control

99

valve does not provide the gradual change in pressure for a given rotation from its closed position that is necessary for fine control of chamber pressure during ion implantation. In fact, with a large area opening and flap, the change in chamber pressure is very rapid as the flap is rotated from its closed position, so that fine control of pressure within a very low pressure range, where the flap must be nearly closed, is very difficult. This problem is solved with the vacuum control valve of FIGS. 94, 95 and 96. The valve includes a flat housing 9410 having a circular opening 9412 through it. A rotatable flap 9420 having a disk shape is supported within the circular opening 9412 by a hinge 9422 attached to the housing 9410. In its closed position, the flap 9420 is co-planar with the flat housing 9410. In order to prevent leakage of plasma through the valve, the gap G between the rotatable flap 9420 and the housing 9410 is narrow while the thickness T of the flap 9420 and housing 9410 is large, much greater than the gap G. For example, the ratio of the thickness T to the gap G is about 10:1. This feature provides the advantage of frictionless operation. In order to provide gradual control of chamber pressure at a very low pressure range (i.e., when the flap 9420 is near its closed position), conically-shaped openings 9430 are provided in the interior surface 9440 of the housing 9410 defining the edge of the opening 9412. Some of the openings 9430 have different axial locations (along the axis of the opening 9412) than others of the openings 9430. In its closed position, the flap 9420 permits virtually zero gas leakage, because the openings 9430 are not exposed. As the flap 9420 begins to rotate from its closed position (i.e., in which the flap 9420 is co-planar with the housing 9410), small portions of at least some of the openings 9430 begin to be exposed, and therefore allow a small amount of gas flow through the valve. As the flap 9420 continues to rotate, it exposes larger portions of the openings 9430. Moreover, it begins to expose others of the

100

openings 9430 not exposed during the earlier phase of its
rotation due to the different axial locations of different
sets of the openings 9430, so that the gas flows through
more of the openings 9430 in proportion to the rotation of
5   the flap 9420. Thus, rotation of the flap 9430 from its
fully closed (co-planar) position causes a continuous but
relatively gradual increase in gas flow through the openings
9430 until the bottom edge 9420a of the flap 9420 reaches
the top surface 9410a of the housing 9410. At this point,
10   all of the openings 9430 are completely exposed so that gas
flow through the openings 9430 is maximum and cannot
increase further. Thus, a continuous gradual increase in
gas flow is achieved (and therefore one that is readily
controlled with a great deal of accuracy) as the flap 9420
15   rotates from its fully closed position to the point at which
the flap bottom edge 9420a is aligned with the housing top
surface 9410a. Within this range of flap rotational
position, fine gradual adjustment of a small total chamber
pressure is provided. Further rotation of the flap 9420
20   creates an annular gap between the periphery of the flap
9420 and the periphery of the large circular opening 9412,
through which gas flow increases as the flap 9420 continues
to rotate.

25   The plural openings 9430 in the opening interior
surface 9440 are semi-circular openings that are tapered so
as to increase in diameter toward the top housing surface
9410a. The tapered semi-circular openings 9430 thus define
semi-conical shapes. However, other suitable shapes may be
30   employed, such as semi-cylindrical, for example. However,
one advantage of the semi-conical shape is that the rate of
increase of gas flow with rotational flap position may be
enhanced as the rotation progresses so that the rate
continues to increase in a fairly smooth manner after the
35   transition point at which the flap bottom edge 9420a passes
the housing top surface 9410a.

Depending upon the desired junction depth, the RF bias
voltage applied to the wafer support pedestal 8025 may be
relatively small (e.g., 500 volts) for a shallow junction or
5   relatively large (e.g., 5,000 volts) for a deep junction.
Some applications may require an RF bias voltage of over
10,000 volts. Such large voltages can cause arcing within
the wafer support pedestal 8025. Such arcing distorts
process conditions in the reactor. In order to enable the
10   wafer support pedestal 8025 to withstand bias voltages as
high a 10,000 volts, for example, without arcing, voids
within the wafer support pedestal 8025 are filled with a
dielectric filler material having a high breakdown voltage,
such as Rexolite®, a product manufactured by C-Lec Plastics,
15   Inc. As illustrated in FIG. 97, the wafer support pedestal
8025 consists of a grounded aluminum base plate 9710, an
aluminum electrostatic chuck plate 9720 and a cylindrical
side wall 9730. Dielectric filler material 9735 fills
voids between the side wall 9730 and the electrostatic chuck
20   plate 9720. Dielectric filler material 9737 fills voids
between the electrostatic chuck plate 9720 and the base
plate 9710. A coaxial RF conductor 9739 carrying the RF
bias power from the RF generator 8065 (not shown in FIG. 97)
is terminated in a narrow cylindrical conductive center plug
25   9740 that fits tightly within a matching conductive
receptacle 9742 of the electrostatic chuck plate 9720. A
wafer lift pin 9744 (one of three) extends through the
pedestal 8025. The lift pin 9744 is tightly held within the
electrostatic chuck plate 9720 by a surrounding blanket 9746
30   of the dielectric filler material. A void 9748 that
accommodates a guide 9750 of the lift pin 9744 is located
entirely within the base plate 9710 so as to minimize the
risk of arcing within the void 9748. Referring to FIG. 98,
bolt 9754 (one of several) holding the base plate 9710 and
35   the electrostatic chuck plate 9720 together is completely
encapsulated to eliminate any voids around the bolt 9754,

102

with dielectric layers 9756, 9758 surrounding exposed
portions of the bolt 9754. The foregoing features have been
found to enable the wafer support pedestal to withstand an
RF bias voltage of over 10,000 volts without experiencing

5   arcing.

FIG. 99 illustrates an ion implantation system
including a plasma immersion ion implantation reactor 9910
of the type illustrated in FIG. 79, 83A, 83B, 84, 85, 88,

10   89A or 93. An independent source 9920 of chamber-cleaning
radicals or gases (such as fluorine-containing gases or
fluorine-containing radicals like NF_3 and/or other cleaning
gases such as hydrogen-containing gases (e.g., H_2 or
compounds of hydrogen) to produce hydrogen-containing

15   radicals or oxygen-containing gases (e.g., O_2) is coupled to
the implant reactor 9910 for use during chamber cleaning
operations. A post-implant anneal chamber 9930 and an ion
beam implanter 9940 are also included in the system of FIG.
99. In addition, an optical metrology chamber 9950 may also

20   be included. Furthermore, a photoresist pyrolization chamber
9952 may be included in the system for removal of the
photoresist mask subsequently after implant and prior to
anneal. Alternatively, this may be accomplished within the
plasma immersion implantation reactor 9910 using the RF

25   plasma source power and optional bias power with oxygen gas,
and/or by using the independent self-cleaning source with
oxygen gas.

The system of FIG. 99 may also include a wet clean

30   chamber 9956 for carrying out wafer cleaning. The wet clean
chamber 9956 may employ such well known wet cleaning species
as HF, for example. The wet clean chamber 9956 may be
employed for pre-implantation or post-implantation cleaning
of the wafer. The pre-implantation cleaning use of the wet

35   clean chamber 9956 may be for removing a thin native oxide
that can accumulate on the wafer between processing

103

operations. The post-implantation cleaning use of the wet
clean chamber 9956 may be for removing photoresist from the
wafer in lieu of the photoresist strip chamber 9952. The
system of FIG. 99 may further include a second, (third,
5   fourth or more) plasma immersion ion implantation reactor
9958 of the type illustrated in FIG. 79, 83A, 83B, 84, 85,
88, 89A or 93. In one example, the first PIII reactor 9910
may be configured to ion implant a first species while the
second PIII reactor 9958 may be configured to implant a
10   second species, so that a single PIII reactor need not be
re-configured to implant the two species in each wafer.
Furthermore, the first and second species may be dopant
impurities for opposite semiconductor conductivity types
(e.g., boron and phosphorus), in which case the second PIII
15   reactor 9958 may be employed in lieu of the beam
implantation tool 9940. Or, two N-type dopants (phosphorous
and arsenic) may be implanted in addition to a P-type dopant
(boron), in which case boron implantation is carried out by
the first PIII reactor 9910, arsenic implantation is carried
20   out in the ion beam tool 9940 and phosphorus implantation is
carried out in the second PIII reactor 9958, for example. In
another example, the 2 (or more) PIII reactors may be
configured to implant the same species so as to increase the
throughput of the system.
25

A wafer transfer robotic handler 9945 transfers
wafers between the plasma ion implant reactor 9910, the
anneal chamber 9930, the ion beam implanter 9940, the
photoresist pyrolization chamber 9952, the optical metrology
30   chamber 9950, the wet clean chamber 9956 and the second PIII
reactor 9958. If the entire system of FIG. 99 is provided
on a single tool or frame, the handler 9945 is a part of
that tool and is supported on the same frame. However, if
some of the components of the system of FIG. 99 are on
35   separate tools located in separate places in a factory, then
the handler 9945 is comprised of individual handlers within

104

each tool or frame and a factory interface that transports wafers between tools within the factory, in the well-known manner. Thus, some or all of the components of the system of FIG. 99 may be provided on a single tool with its own

5   wafer handler 9945. Alternatively, some or all of the components of the system of FIG. 99 may be provided on respective tools, in which case the wafer handler 9945 includes the factory interface.

10   The process controller 8075 can receive measurements of a previously implanted wafer from the optical metrology chamber 9950, and adjust the implant process in the plasma implant reactor 9910 for later wafers. The process controller 8075 can use established data mining

15   techniques for process correction and control. The inclusion of the ion beam implanter 9940 permits the system to perform all of the ion implantation steps required in semiconductor fabrication, including implantation of light elements (such as boron or phosphorous) by the plasma ion

20   implant reactor 9910 and implantation of heavier elements (such as arsenic) by the ion beam implanter 9940. The system of FIG. 99 may be simplified. For example, a first version consists of only the chamber cleaning radical source 9920, the PIII reactor 9910 and the process controller 8075.

25   A second version includes the foregoing elements of the first version and, in addition, the optical metrology tool 9950. A third version includes the foregoing elements of the second version and, in addition, the ion beam implanter 9940 and/or the second PIII reactor 9958. A fourth version

30   includes the foregoing elements of the third version and, in addition, the anneal chamber 9930.

Ion Implantation Performance Of The Torroidal Source:
          The plasma immersion ion implantation (PIII) reactor of

35   FIG. 85 realizes many advantages not found heretofore in a single reactor. Specifically, the PIII reactor of FIG. 85

105

has low minimum ion implant energy (because it has a low plasma potential), low contamination (because the recirculating plasma generally does not need to interact with chamber surfaces to provide a ground return), very good

5   control over unwanted etching (because it exhibits low fluorine dissociation), and excellent control over ion implant flux (because it exhibits a nearly linear response of plasma electron density to source power).

10   The advantage of excellent control over ion implant flux is illustrated in the graph of FIG. 100, in which electron density is plotted as a function of source power level for the torroidal source PIII reactor of FIG. 85 and for an inductively coupled PIII reactor of the type

15   illustrated in FIG. 79. Electron density is an indicator of plasma ion density and therefore of the ion implant flux or implant dose to the wafer. The inductively coupled source of the PIII reactor of FIG. 79 tends to have a highly non-linear response of electron density to applied source power,

20   exhibiting a sudden increase in electron density at a threshold power level, PICP, below which the slope (response) is negligible and above which the slope (response) is so steep that electron density (and therefore ion implant flux or dose) is nearly impossible to control to

25   any fine degree. In contrast the torroidal source PIII reactor of FIG. 85 has a generally linear and gradual response of electron density to source power level above a threshold power level PTH, so that ion implant flux (dose) is readily controlled to within a very fine accuracy even at

30   very high source power level. It should be noted here that the plasma source power level of the torroidal source PIII reactor of FIG. 85 is a function of the two different source power generators 8055, 8056 coupled to the respective reentrant conduits 8150, 8151. The source power frequency

35   may be about 13.56 MHz, although the frequency of each of the two source power generators 8055, 8056 are offset from

this frequency (13.56 MHz) by +100 kHz and -100 kHz, respectively, so that the two torroidal plasma current paths established by the sources 8110 and 8111 are decoupled from one another by being de-tuned from one another by about 200 kHz. However, their power levels may be generally about the same. Operating frequencies are not limited to the regime described here, and another RF frequency and frequency offset may be selected for the pair of RF source power generators 8055, 5056.

The advantage of low fluorine dissociation of the PIII reactor of FIG. 85 is important in preventing unwanted etching that can occur when a fluorine-containing dopant gas, such as BF3, is employed. The problem is that if the BF3 plasma by-products are dissociated into the simpler fluorine compounds, including free fluorine, the etch rate increases uncontrollably. This problem is solved in the PIII reactor of FIG. 85 by limiting the fluorine dissociation even at high power levels and high plasma density. This advantage is illustrated in the graph of FIG. 101, in which free fluorine density (an indicator of fluorine dissociation) is plotted as a function of source power for the PIII reactor of FIG. 85 and for the inductively coupled reactor of FIG. 79 for the sake of comparison. The inductively coupled reactor of FIG. 79 exhibits an extremely sudden increase in free fluorine density above a particular source power level, PDIS, above which the dissociation increases at a very high rate of change, and is therefore difficult to control. In contrast, the PIII reactor of FIG. 85 exhibits generally linear and nearly negligible (very gradual) increase in free fluorine density above a threshold source power PTH. As a result, there is very little unwanted etching during ion implantation with fluorine-containing dopant gases in the torroidal source PIII reactor of FIG. 85. The etching is further minimized if the temperature of the wafer is held to

a low temperature, such as below 100 degrees C, or more preferably below 60 degrees C, or most preferably below 20 degrees C. For this purpose, the wafer pedestal 8025 may be an electrostatic chuck that holds and releases the wafer

5   electrostatically with thermal control cooling apparatus 8025a and/or heating apparatus 8025b that control the temperature of a semiconductor wafer or workpiece held on the top surface of the wafer support pedestal 8025.   Some small residual etching (such as may be realized with the

10   torroidal source PIII reactor of FIG. 85) is acceptable and may actually prevent the deposition of unwanted films on the wafer during ion implantation. During ion implantation, some plasma by-products may deposit as films on the wafer surface during ion implantation. This is particularly true

15   in cases where the implantation process is carried out at a very low ion energy (low bias voltage) and particularly with a dopant gas consisting of a hydride of the dopant species (e.g., a hydride of boron or a hydride of phosphorous). In order to further reduce unwanted depositions that normally

20   occur with hydride dopants (e.g., B_2H_6, PH_3), one aspect of the process is to add hydrogen and/or helium to the dopant gas to eliminate the deposition on the surface of the wafer. However, the requisite etch rate to compete with such an unwanted deposition is very low, such as that exhibited by

25   the torroidal source PIII reactor of FIG. 85.

The advantage of a low minimum ion implant energy increases the range of junction depths of which the PIII reactor of FIG. 85 is capable (by reducing the lower limit

30   of that range). This advantage is illustrated in the graph of FIG. 102, in which plasma potential is plotted as a function of plasma source power for the torroidal source PIII reactor of FIG. 85 and for the capacitively coupled PIII reactor of FIG. 83A, for the sake of comparison. The

35   plasma potential is the potential on ions at the wafer surface due to the plasma electric field in the absence of

108

any bias voltage on the wafer, and therefore is an indicator
of the minimum energy at which ions can be implanted. FIG.
102 shows that the plasma potential increases indefinitely
as the source power is increased in the capacitively coupled
5   PIII reactor of FIG. 83A, so that in this reactor the
minimum implant energy is greatly increased (the implant
energy/depth range is reduced) at high plasma density or ion
implant flux levels. In contrast, above a threshold power
PTH, the torroidal source PIII reactor of FIG. 85 exhibits a
10   very gradual (nearly imperceptible) increase in plasma
potential as source power is increased, so that the plasma
potential is very low even at high plasma source power or
ion density (high ion implant flux). Therefore, the range
of plasma ion energy (ion implant depth) is much larger in
15   the PIII reactor of FIG. 85 because the minimum energy
remains very low even at high ion flux levels.

The plasma potential in the capacitively coupled PIII
reactor of FIG. 83A can be reduced by increasing the source
20   power frequency. However, this becomes more difficult as
the junction depth and corresponding ion energy is reduced.
For example, to reach a plasma potential that is less than
500 eV (for a 0.5 kV Boron implant energy), the source power
frequency would need to be increased well into the VHF range
25   and possibly above the VHF range. In contrast, the source
power frequency of the torroidal source PIII reactor of FIG.
85 can be in the HF range (e.g., 13 MHz) while providing a
low plasma potential.

30   A further advantage of the torroidal source PIII
reactor of FIG. 85 over the capacitively coupled source PIII
reactor of FIG. 83A is that the torroidal source PIII
reactor has a thinner plasma sheath in which proportionately
fewer inelastic collisions of ions occur that tend to skew
35   the ion implant energy distribution. This thinner sheath
may be nearly collisionless. In contrast, the capacitively

109

coupled source PIII reactor of FIG. 83A generates plasma
ions in the sheath by an HF or VHF RF source that tends to
produce a much thicker sheath. The thicker sheath produces
far more collisions that significantly skew ion energy
5   distribution. The result is that the ion implanted junction
profile is far less abrupt. This problem is more acute at
lower ion energies (shallower implanted junctions) where the
skew in energy produced by the collisions in the thicker
sheath represent a far greater fraction of the total ion
10   energy. The torroidal source PIII reactor of FIG. 85
therefore has more precise control over ion implant energy
and is capable of producing implanted junctions with greater
abruptness, particularly for the more shallow junctions that
are needed for the more advanced (smaller feature size)
15   technologies.

A related advantage of the torroidal source PIII
reactor of FIG. 85 is that it can be operated at much lower
chamber pressures than the capacitively coupled PIII reactor
20   of FIG. 83A. The capacitively coupled PIII reactor of FIG.
83A requires a thicker sheath to generate plasma ions in the
sheath, which in turn requires higher chamber pressures
(e.g., 10-100 mT). The torroidal source PIII reactor of
FIG. 85 does not need to generate plasma near the sheath
25   with bias power and for many applications therefore is best
operated with a thinner (nearly collisionless) sheath, so
that chamber pressures can be very low (e.g., 1-3 mT). This
has the advantage of a wider ion implantation process window
in the torroidal source PIII reactor. However, as will be
30   discussed with reference to doping of a three dimensional
structure such as a polysilicon gate having both a top
surface and vertical side walls, velocity scattering of
dopant ions in the sheath enables ions to implant not only
the top surface of the polysilicon gate but also implant its
35   side walls. Such a process may be referred to as conformal
ion implanting. Conformal ion implanting has the advantage

110

of doping the gate more isotropically and reducing carrier
depletion at the gate-to-thin oxide interface, as will be
discussed below. Therefore, some sheath thickness is
desirable in order to scatter a fraction of the dopant ions
5   away from a purely vertical trajectory so that the scattered
fraction implants into the side walls of the polysilicon
gate. (In contrast, in an ion beam implanter, such
scattering is not a feature, so that only the gate top
surface is implanted.) Another advantage of a plasma sheath
10   of finite thickness (and therefore finite collisional cross-
section) is that some very slight scattering of all the ions
from a purely vertical trajectory (i.e., a deflection of
only a few degrees) may be desirable in some cases to avoid
implanting along an axis of the wafer crystal, which could
15   lead to channeling or an implant that is too deep or a less
abrupt junction profile. Also, scattering of the ions leads
to placement of dopants under the polysilicon gate. This
can be very useful in optimizing CMOS device performance by
controlling the dopant overlap under the poly Si gate and
20   Source drain extension areas, as will be discussed later in
this specification in more detail.

     The low contamination exhibited by the torroidal source
PIII reactor of FIG. 85 is due primarily to the tendency of
25   the plasma to not interact with chamber surfaces and instead
oscillate or circulate in the torroidal paths that are
generally parallel to the chamber surfaces rather than being
towards those surfaces. Specifically, the pair torroidal
paths followed by the plasma current are parallel to the
30   surfaces of the respect reentrant conduits 8150, 8151 of
FIG. 85 and parallel to the interior surface of the ceiling
8015 and of the wafer support pedestal 8025. In contrast,
the plasma source power generates electric fields within the
capacitively coupled PIII reactor of FIG. 83A that are
35   oriented directly toward the ceiling and toward the chamber
walls.

In the torroidal source PIII reactor of FIG. 85, the
only significant electric field oriented directly toward a
chamber surface is produced by the bias voltage applied to
  5   the wafer support pedestal 8025, but this electric field
does not significantly generate plasma in the embodiment of
FIG. 85. While the bias voltage can be a D.C. (or pulsed
D.C.) bias voltage, in the embodiment of FIG. 85 the bias
voltage is an RF voltage. The frequency of the RF bias
 10   voltage can be sufficiently low so that the plasma sheath at
the wafer surface does not participate significantly in
plasma generation. Thus, plasma generation in the torroidal
source PIII reactor of FIG. 85 produces only plasma currents
that are generally parallel to the interior chamber
 15   surfaces, and thus less likely to interact with chamber
surfaces and produce contamination.

Further reduction of metal contamination of ion implantation
processes is achieved by first depositing a passivation
 20   layer on all chamber surfaces prior to performing the ion
implantation process. The passivation layer may be a
silicon-containing layer such as silicon dioxide, silicon
nitride, silicon, silicon carbide, silicon hydride, silicon
fluoride, boron or phosphorous or arsenic doped silicon,
 25   boron or phosphorous or arsenic doped silicon carbide, boron
or phosphorous or arsenic doped silicon oxide.
Alternatively, the passivation may be a fluorocarbon or
hydrocarbon or hydrofluorocarbon film. Compounds of
germanium may also be used for passivation. Alternatively,
 30   the passivation layer may be a dopant-containing layer such
as boron, phosphorous, arsenic or antimony formed by
decomposition of a compound of the dopant precursor gas,
such as BF_3, B_2H_6, PF_3, PF_5, PH_3, AsF_3, of AsH_3. It may be
advantageous to form a passivation layer with a source gas
 35   or source gas mixture using gas(es)similar to that or those
that are to be used in the subsequent plasma immersion
                            112

implantation process step. (This may reduce unwanted etching
of the passivation layer by the subsequent implant process
step.) Alternatively, it may be advantageous to combine the
fluoride and the hydride of a particular gas to minimize the
5   fluorine and/or hydrogen incorporated in the passivation
layer, for example, $BF_3+B_2H_6$, PH_3+PF_3, AsF_3+AsH_3, SiF_4+SiH_4, or
GeF_4+GeH_4.

While the RF bias frequency of the torroidal source
10   PIII reactor of FIG. 85 is sufficiently low to not affect
plasma generation by the plasma source power applicators
8110, 8111, it is also sufficiently low to permit the ions
in the plasma sheath to follow the sheath oscillations and
thereby acquire a kinetic energy of up to the equivalent to
15   the full peak-to-peak voltage of the RF bias power applied
to the sheath, depending upon pressure and sheath thickness.
This reduces the amount of RF bias power required to produce
a particular ion energy or implant depth. On the other
hand, the RF bias frequency is sufficiently high to avoid
20   significant voltage drops across dielectric layers on the
wafer support pedestal 8025, on chamber interior walls and
on the wafer itself. This is particularly important in ion
implantation of very shallow junctions, in which the RF bias
voltage is correspondingly small, such as about 150 volts
25   for a 100 Angstrom junction depth (for example). An RF
voltage drop of 50 volts out of a total of 150 volts across
the sheath (for example) would be unacceptable, as this
would be a third of the total sheath voltage. The RF bias
frequency is therefore sufficiently high to reduce the
30   capacitive reactance across dielectric layers so as to limit
the voltage drop across such a layer to less than on the
order of 10% of the total RF bias voltage. A frequency
sufficiently high meet this latter requirement while being
sufficiently low for the ions to follow the sheath
35   oscillations is in the range of 100 kHz to 10 MHz, and more
optimally in the range of 500 kHz to 5 MHz, and most

113

optimally about 2 MHz. One advantage of reducing capacitive
voltage drops across the wafer pedestal is that the sheath
voltage can be more accurately estimated from the voltage
applied to the pedestal. Such capacitive voltage drops can
5   be across dielectric layers on the front or back of the
wafer, on the top of the wafer pedestal and (in the case of
an electrostatic chuck) the dielectric layer at the top of
the chuck.

10   Ion implantation results produced by the torroidal
source PIII reactor of FIG. 85 compare favorably with those
obtained with a conventional beam implanter operated in
drift mode, which is much slower than the PIII reactor.
Referring to FIG. 103, the curves "A" and "a" are plots of
15   dopant (boron) volume concentration in the wafer crystal as
a function of depth for boron equivalent energies of 0.5
keV. (As will be discussed below, to achieve the same ion
energy as the beam implanter, the bias voltage in the PIII
reactor must be twice the acceleration voltage of the beam
20   implanter.) Even though the PIII reactor (curve "A") is
four times faster than the beam implanter (curve "B"), the
implant profile is nearly the same, with the same junction
abruptness of about 3 nanometers (change in junction depth)
per decade (of dopant volume concentration) and junction
25   depth (about 100 Angstroms). Curves "B" and "b" compare the
PIII reactor results ("B") with those of a conventional beam
implanter ("b") at boron equivalent energies of 2 keV,
showing that the junction abruptness and the junction depth
(about 300 Angstroms) is the same in both cases.   Curves
30   "C" and "c" compare the PIII reactor results ("C") with
those of a conventional beam implanter ("c") at boron
equivalent energies of 3.5 keV, showing that the junction
depth (about 500 Angstroms) is the same in both cases.

35   FIG. 103 compares the PIII reactor performance with the
conventional beam implanter operated in drift mode (in which

the beam voltage corresponds to the desired junction depth).
Drift mode is very slow because the beam flux is low at
such low beam energies. This can be addressed by using a
much higher beam voltage and then decelerating the beam down

5   to the correct energy before it impacts the wafer. The
deceleration process is not complete, and therefore leaves
an energy "contamination" tail (curve "A" of FIG., 104)
which can be reduced by rapid thermal annealing to a better
implant profile with greater abruptness (curve "B" of FIG.

10   104). Greater activated implanted dopant concentration,
however, can be achieved using a dynamic surface annealing
process employing localized melting or nearly melting
temperatures for very short durations. The dynamic surface
annealing process does not reduce energy contamination

15   tails, such as the energy contamination tail of curve "C" of
FIG. 105. In comparison, the torroidal source PIII reactor
of FIG. 85 needs no deceleration process since the bias
voltage corresponds to the desired implant depth, and
therefore has no energy contamination tail (curve "D" of

20   FIG. 105). Therefore, the PIII reactor can be used with the
dynamic surface anneal process to form very abrupt ultra
shallow junction profile, while the conventional beam
implanter operating in deceleration mode cannot. The
dynamic surface annealing process consists of locally

25   heating regions of the wafer surface to nearly (e.g., within
100 to 50 degrees of) its melting temperature for very short
durations (e.g., nano-seconds to tens of milliseconds) by
scanning a laser beam or a group of laser beams across the
wafer surface.

30

FIG. 106 illustrates how much greater a dopant
concentration can be attained with the dynamic surface
annealing process. Curve "A" of FIG. 106 illustrates the
wafer resistivity in Ohms per square as a function of

35   junction depth using a beam implanter and a rapid thermal
anneal of the wafer at 1050 degrees C. The concentration of

dopant reached 10E20 per cubic centimeter. Curve "B" of
FIG. 106 illustrates the wafer resistivity in Ohms per
square as a function of junction depth using the torroidal
source PIII reactor of FIG. 85 and a dynamic surface anneal

5   process after implanting at a temperature of 1300 degrees C.
The concentration of the dopant reached 5×10^{20} following the
dynamic surface annealing, or about five times that achieved
with rapid thermal annealing. FIG. 107 illustrates how
little the implanted dopant profile changes during dynamic

10 surface annealing. Curve "A" of FIG. 107 is the dopant
distribution prior to annealing while curve "B" of FIG. 107
is the dopant distribution after annealing. The dynamic
surface annealing process causes the dopant to diffuse less
than 10 Å, while it does not adversely affect the junction

15 abruptness, which is less than 3.5 nm/decade. This tendency
of the dynamic surface annealing process to minimize dopant
diffusion facilitates the formation of extremely shallow
junctions. More shallow junctions are required (as source-
to-drain channel lengths are decreased in higher speed

20 devices) in order to avoid source-to-drain leakage currents.
On the other hand, the shallower junction require much
higher active dopant concentrations (to avoid increased
resistance) that can best be realized with dynamic surface
annealing. As discussed elsewhere in this specification,

25 junction depth can be reduced by carrying out a wafer
amorphization step in which the wafer is bombarded with ions
(such as silicon or germanium ions) to create lattice
defects in the semiconductor crystal of the wafer. We have
implanted and annealed junctions having a high dopant

30 concentration corresponding to a low resistivity (500 Ohms
per square), an extremely shallow junction depth (185 Å) and
a very steep abruptness (less than 4nm/decade). In some
cases, the depth of the amorphizing or ion bombardment
process may extend below the dopant implant junction depth.

35 For example, amorphization using SiF4 gas and a 10 kV peak-
to-peak bias voltage in the PIII reactor of FIG. 85 forms an

116

amorphized layer to a depth of about 150 Angstroms, while
dopant (boron) ions accelerated across a 1000 peak-to-peak
volt sheath (bias) voltage implant to a depth of only about
100 Angstroms.

5

FIG. 108 illustrates the bias voltage for the torroidal
source PIII reactor (left hand ordinate) and the beam
voltage for the ion beam implanter (right hand ordinate) as
a function of junction depth. The PIII reactor and the beam
10 implanter produce virtually identical results provided the
PIII reactor bias voltage is twice the beam voltage.

Working Examples:
15   A principal application of a PIII reactor is the
formation of PN junctions in semiconductor crystals. FIGS.
109 and 110 illustrate different stages in the deposition of
dopant impurities in the fabrication of a P-channel metal
oxide semiconductor field effect transistor (MOSFET).
20 Referring first to FIG. 109, a region 9960 of a
semiconductor (e.g., silicon) wafer may be doped with an N-
type conductivity impurity, such as arsenic or phosphorus,
the region 9960 being labeled "n" in the drawing of FIG. 109
to denote its conductivity type. A very thin silicon
25 dioxide layer 9962 is deposited on the surface of the wafer
including over n-type region 9960. A polycrystalline
silicon gate 9964 is formed over the thin oxide layer 9962
from a blanket polysilicon layer that has been doped with
boron in the PIII reactor. After formation of the gate
30 9964, p-type dopant is implanted in the PIII reactor to form
source and drain extensions 9972 and 9973. Spacer layers
9966 of a dielectric material such as silicon dioxide and/or
silicon nitride (for example) are formed along two opposite
vertical sides 9964a, 9964b of the gate 9964. Using the
35 PIII reactor of FIG. 85 with a process gas consisting of BF3
or B2H6 (for example), boron is implanted over the entire N-

117

type region 9960. The spacer layers mask their underlying regions from the boron, so that P-type conductivity source and drain contact regions 9968, 9969 are formed on either side of the gate 9964, as shown in FIG. 110. This step is

5   carried out with a boron-containing species energy in the range of 2 to 10 kVpp on the RF bias voltage (controlled by the RF bias power generator 8065 of FIG. 85). In accordance with the example of FIG. 108, the RF bias voltage on the wafer pedestal 8025 in the PIII reactor of FIG. 85 is twice

10 the desired boron energy. The implantation is carried out for a sufficient time and at a sufficient ion flux or ion density (controlled by the RF source power generators 8055, 8056 of FIG. 85) to achieve a surface concentration of boron exceeding 5×10^{15} atoms per square centimeter. The

15 concentration of boron in the gate 9964 is then increased to 1×10^{16} atoms per square centimeter by masking the source and drain contacts 9968, 9969 (by depositing a layer of photoresist thereover, for example) and carrying out a further (supplementary) implantation step of boron until the

20 concentration of boron in the gate 9964 reaches the desired level (1×10^{16} atoms/cubic centimeter). The source and drain contacts 9968, 9969 are not raised to the higher dopant concentration (as is the gate 9964) because the higher dopant concentration may be incompatible with

25 formation of a metal silicide layer (during a later step) over each contact 9968, 9969. However, the gate 9964 must be raised to this higher dopant concentration level in order to reduce carrier depletion in the gate 9964 near the interface between the gate 9964 and the thin silicon dioxide

30 layer 9962. Such carrier depletion in the gate would impede the switching speed of the transistor. The dopant profile in the gate must be highly abrupt in order attain a high dopant concentration in the gate 9964 near the thin oxide layer 9962 without implanting dopant into the underlying

35 thin oxide layer 9962 or into the source-to-drain channel underlying the thin oxide layer 9962. Another measure that

118

can be taken to further enhance gate performance and device
speed is to raise the dielectric constant of the thin
silicon dioxide layer 9962 by implanting nitrogen in the
thin silicon dioxide layer 9962 so that (upon annealing)
5   nitrogen atoms replace oxygen atoms in the layer 9962, as
will be described later in this specification. A further
measure for enhancing gate performance is conformal
implanting in which dopant ions that have been deflected
from their vertical trajectory by collisions in the plasma
10   sheath over the wafer surface are able to implant into the
vertical side walls of the gate 9964. This further
increases the dopant concentration in the gate 9964 near the
interface with the thin oxide layer 9962, and provide a more
uniform and isotropic dopant distribution within the gate.
15   A yet further measure for enhancing gate performance for
gates of N-channel devices implanted with arsenic is to
implant phosphorus during the supplementary implant step
using the PIII reactor. The phosphorus is lighter than
arsenic and so diffuses more readily throughout the
20   semiconductor crystal, to provide less abrupt junction
profile in the source drain contact areas.

The depth of the ion implantation of the source and
drain contacts 9968, 9969 may be in the range of 400 to 800
25   Å. If the gate 9964 is thinner than that, then the gate
9964 must be implanted in a separate implantation step to a
lesser depth to avoid implanting any dopant in the thin
oxide layer 9962 below the gate 9964. In order to avoid
depletion in the region of the gate 9964 adjacent the thin
30   oxide layer 9962, the implantation of the gate must extend
as close to the gate/oxide interface as possible without
entering the thin oxide layer 9962. Therefore, the implant
profile of the gate must have the highest possible
abruptness (e.g., 3 nm/decade or less) and a higher dopant
35   dose (i.e., 1 x 10^{16} atoms/cm^2).

Referring now to FIG. 110, source and drain extensions 9972, 9973 are typically formed before depositing and forming the spacer layers 9966 of FIG. 109. The extensions layers are formed by carrying out a more shallow and light implant of boron over the entire region 9960. Typically, the junction depth of the source and drain extensions is only about 100 to 300 Angstroms and the implant dose is less than 5×10^{15} atoms/square centimeter. This implant step, therefore, has little effect on the dopant profiles in the gate 9964 or in the source and drain contacts 9968, 9969, so that these areas need not be masked during the implantation of the source and drain extensions 9972, 9973. However, if masking is desired, then it may be carried out with photoresist. The source and drain extensions are implanted at an equivalent boron energy of 0.5 kV, requiring a 1.0 kVpp RF bias voltage on the wafer pedestal 8025 of FIG. 85.

The same structures illustrated in FIGS. 109 and 110 are formed in the fabrication of an N-channel MOSFET. However, the region 9960 is initially doped with a P-type conductivity such as boron and is therefore a P-type conductivity region. And, the implantation of the gate 9964 and of the source and drain contacts 9968, 9969 (illustrated in FIG. 109) is carried out in a beam implanter (rather than in a PIII reactor) with an N-type conductivity impurity dopant such as arsenic. Furthermore, the supplementary implantation of the gate 9964 that raises its dopant dose concentration to 1×10^{16} atoms/ cm^2 is carried out in the PIII reactor with phosphorus (rather than arsenic) using a phosphorus-containing process gas. Phosphorus is preferred for this latter implantation step because it diffuses more uniformly than arsenic, and therefore enhances the quality of the N-type dopant profile in the gates 9964 of the N-channel devices. The ion beam voltage is in the range of 15-30 kV for the arsenic implant step (simultaneous implanting of the N-channel source and drain contacts 9968,

120

9969 and of the N-channel gates 9964), and is applied for a
sufficient time to reach a dopant surface concentration
exceeding 5 x 10^{15} atoms per cubic centimeter. The
supplementary gate implant of phosphorus is carried out at
5   an ion beam voltage in the range of only 2-5 kV for a
sufficient time to raise the dopant surface concentration in
the N-channel gates to 1 x 10^{16} atoms/cubic cm.

The implantation steps involving phosphorus and boron
10   are advantageously carried out in the PIII reactor rather
than an ion beam implanter because the ion energies of these
light elements are so low that ion flux in a beam implanter
would be very low and the implant times would be
inordinately high (e.g., half and hour per wafer). In the
15   PIII reactor, the source power can be 800 Watts at 13.56 MHz
(with the 200 kHz offset between the two torroidal plasma
currents as described above), the implant step being carried
out for only 5 to 40 seconds per wafer.

20   The sequence of ion implantation steps depicted in
FIGS. 109 and 110 may be modified, in that the light shallow
source and drain extension implant step of FIG. 110 may be
carried out before or after formation of the spacer layer
9966 and subsequent heavy implantation of the contacts 9968,
25   9969 and gate 9964. When extension implants are done after
the spacer layer 9966 is formed, the spacer layer 9966 must
be removed before the extension implants are performed.

One example of a process for fabricating complementary
30   MOSFETS (CMOS FETs) is illustrated in FIG. 111. In the
first step (block 9980), the P-well and N-well regions of
the CMOS device are implanted in separate steps. Then, a
blanket thin gate oxide layer and an overlying blanket
polysilicon gate layer are formed over the entire wafer
35   (block 9981 of FIG. 111). The P-well regions are masked and
the N-well regions are left exposed (block 9982). The

121

portions of the polysilicon gate layer lying in the N-well regions are then implanted with boron in a PIII reactor (block 9983). The P-channel gates (9964 in FIG. 109) are then photolithographically defined and etched, to expose

5 portions of the silicon wafer (block 9984). Source and drain extensions 9972, 9973 of FIG. 109 self-aligned with the gate 9964 are then formed by ion implantation of boron using the PIII reactor (block 9985). A so-called "halo" implant step is then performed to implant an N-type dopant

10 under the edges of each P-channel gate 9964 (block 9986). This is done by implanting arsenic using an ion beam tilted at about 30 degrees from a vertical direction relative to the wafer surface and rotating the wafer. Alternatively, this step may be accomplished by implanting phosphorus in

15 the PIII reactor using a chamber pressure and bias voltage conducive to a large sheath thickness to promote collisions in the sheath that divert the boron ions from a vertical trajectory. Then, the spacer layers 9986 are formed over the source drain extensions 9972, 9973 (block 9987) and

20 boron is then implanted at a higher energy to form the deep source drain contacts 9969 (block 9988), resulting in the structure of FIG. 110. The reverse of step 9982 is then performed by masking the N-well regions (i.e., the P-channel devices) and exposing the P-well regions (block 9992).

25 Thereafter steps 9993 through 9998 are performed that correspond to steps 9983 through 9988 that have already been described, except that they are carried out in the P-well regions rather than in the N-well regions, the dopant is Arsenic rather than Boron, and a beam line ion implanter is

30 employed rather than a PIII reactor. And, for the N-channel device halo implant of block 9996 (corresponding to the P-channel device halo implant of block 9986 described above), the dopant is a P-type dopant such as boron. In the case of the N-channel devices implanted in steps 9993 through 9998,

35 a further implant step is performed, namely a supplemental implant step (block 9999) to increase the dose in the

122

polysilicon gate as discussed above in this specification. In the supplemental implantation step of block 9999, phosphorus is the N-type dopant impurity and is implanted using a PIII reactor rather than a beam implanter (although

5 a beam implanter could be employed instead).

       As noted above, the process may be reversed so that the gate 9964 and source and drain contacts 9968, 9969 are implanted before the source and drain extensions 9972, 9973.

10

       After all ion implantations have been carried out, the wafer is subjected to an annealing process such as spike annealing using rapid thermal processing (RTP) and/or the dynamic surface annealing (DSA) process discussed earlier in

15 this specification. Such an annealing process causes the implanted dopant ions, most of which came to rest in interstitial locations in the crystal lattice, to move to atomic sites, i.e., be substituted for silicon atoms originally occupying those sites. More than one annealing

20 step can be used to form the pmos and nmos devices and these steps can be inserted in the process flow as appropriate from activation and diffusion point of view.

       The foregoing ion implantation processes involving the

25 lighter atomic elements (e.g., boron and phosphorus) are carried out using a PIII reactor in the modes described previously. For example, the bias power frequency is selected to maximize ion energy while simultaneously providing low impedance coupling across dielectric layers.

30 How this is accomplished is described above in this specification.

       The ion implantation processes described above are enhanced by other processes. Specifically, in order to

35 prevent channeling and in order to enhance the fraction of implanted ions that become substitutional upon annealing,

123

the semiconductor wafer crystal may be subjected to an ion bombardment process that partially amorphizes the crystal by creating crystal defects. The ions employed should be compatible with the wafer material, and may be formed in the PIII reactor in a plasma generated from one or more of the following gases: silicon fluoride, silicon hydride, germanium fluoride, germanium hydride, Xenon, Argon, or carbon fluoride (ie. tetrafluoromethane, octafluorocyclobutane, etc) or carbon hydride (ie. methane, acetylene, etc) or carbon hydride/fluoride (ie. tetrafluoroethane, difluoroethylene, etc) gases. One advantage of the PIII reactor is that its implant processes are not mass selective (unlike an ion beam implanter). Therefore, during ion implantation of a dopant impurity such boron, any other element may also be implanted simultaneously, regardless of ion mass in the PIII reactor. Therefore, unlike an ion beam implanter, the PIII reactor is capable of simultaneously implanting a dopant impurity while carrying out an amorphizing process. This may be accomplished using a BF3 gas (to provide the dopant ions) mixed with an SiF4 gas (to provided the amorphizing bombardment ion species). Such a simultaneous ion implantation process is referred to as a co-implant process. The amorphization process may also be carried out sequentially with the doping process. In addition to amorphization, simultaneous implants of dopant and non-dopant atoms such as Fluorine, Germanium, Carbon or other elements are done to change the chemistry of the Silicon wafer. This change in chemistry can help in increasing dopant activation and reducing dopant diffusion.

Another process that can be carried out in the PIII reactor is a surface enhancement process in which certain ions are implanted in order to replace other elements in the crystal. One example of such a surface enhancement process is nitrodization. In this process, the dielectric constant

124

of the thin silicon dioxide layer 9962 is increased (in
order to increase device speed) by replacing a significant
fraction of the oxygen atoms in the silicon dioxide film
with nitrogen atoms. This is accomplished in the PIII
5   reactor by generating a plasma from a nitrogen-containing
gas, such as ammonia, and implanting the nitrogen atoms into
the silicon dioxide layer 9962. This step may be performed
at any time, including before, during and/or after the
implantation of the dopant impurity species. If the
10 nitrodization process is performed at least partially
simultaneously with the dopant ion implant step, then the
nitrodization process is a co-implant process. Since the
ion implantation process of the PIII reactor is not mass
selective, the co-implant process may be carried out with
15 any suitable species without requiring that it atomic weight
be the same as or related to the atomic weight of the dopant
implant species. Thus, for example, the dopant species,
boron, and the surface enhancement species, nitrogen, have
quite different atomic weights, and yet they are implanted
20 simultaneously in the PIII reactor. Typically nitrodization
is performed without implanting dopant atoms.

A further process related to ion implantation is
surface passivation. In this process, the interior surfaces
25 of the reactor chamber, including the walls and ceiling, are
coated with a silicon-containing passivation material (such
as silicon dioxide or silicon nitride or silicon hydride)
prior to the introduction of a production wafer. The
passivation layer prevents the plasma from interacting with
30 or sputtering any metal surfaces within the plasma reactor.
The deposition the passivation layer is carried out by
igniting a plasma within the reactor from a silicon
containing gas such as silane mixed with oxygen, for
example. This passivation step, combined with the low-
35 contamination torroidal source PIII reactor of FIG. 85, has
yielded extremely low metal contamination of a silicon wafer

during ion implantation, about 100 times lower than that
typically obtained in a conventional beam implanter.

Upon completion of the ion implantation process, the
passivation layer is removed, using a suitable etchant gas
such as NF3 which may be combined with a suitable ion
bombardment gas source such as argon oxygen, or hydrogen.
During this cleaning step, the chamber surfaces may be
heated to 60 degrees C or higher to enhance the cleaning
process. A new passivation layer is deposited before the
next ion implantation step.

Alternatively, a new passivation layer may be deposited
before implanting a sequence of wafers, and following the
processing of the sequence, the passivation layer and other
depositions may be removed using a cleaning gas.

FIG. 112 is a flow diagram showing the different
options of combining the foregoing ion implantation-related
processes with the dopant implantation processes of FIG.
111. A first step is cleaning the chamber to remove
contamination or to remove a previously deposited
passivation layer (block 9001 of FIG. 112). Next, a
passivation layer of silicon dioxide, for example, is
deposited over the interior surfaces of the chamber (block
9002) prior to the introduction of the wafer to be
processed. Next, the wafer is introduced into the PIII
reactor chamber and may be subjected to a cleaning or
etching process to remove thin oxidation layers that may
have accumulated on the exposed semiconductor surfaces in
the brief interim since the wafer was last processed (block
9003). A pre-implant wafer amorphizing process may be
carried out (block 9004) by ion-bombarding exposed surfaces
of the wafer with silicon ions, for example. A pre-implant
surface enhancement process may also be carried out (block
9005) by implanting a species such as nitrogen into silicon
dioxide films. The dopant implantation process may then be

126

carried out (block 9006). This step is an individual one of the boron or phosphorus implant steps illustrated in the general process flow diagram of FIG. 111. During the dopant implant process of block 9006, other ions in addition to the dopant ions may be implanted simultaneously in a co-implant process (block 9007). Such a co-implant process (9007) may be an amorphizing process, a light etch process that prevents accumulation of plasma by-products on the wafer surface, enhancing dopant activation and reducing dopant diffusion, or surface enhancement process. After completion of the dopant ion implant process (9006) and any co-implant process (9007), various post implant processes may be carried out. Such post implant processes may include a surface enhancement process (block 9008). Upon completion of all implant steps (including the step of block 9008), an implant anneal process is carried out (block 9012) after removing any photo-resist mask layers on the wafer in the preceding wafer clean step of block 9009. This anneal process can be a dynamic surface anneal in which a laser beam (or several laser beams) are scanned across the wafer surface to locally heat the surface to nearly melting temperature (about 1300 degrees C) or to melting temperature, each local area being heated for an extremely short period of time (e.g., on the order of nanoseconds to tens of milliseconds). Other post implant processes carried out after the anneal step of block 9112 may include a wafer cleaning process (block 9009) to remove layers of plasma by-products deposited during the ion implantation process, deposition of a temporary passivation coating on the wafer to stabilize the wafer surface (block 9010) and a chamber cleaning process (block 9011), carried out after removal of the wafer from the PIII reactor chamber, for removing a previously deposited passivation layer from the chamber interior surfaces.

While the invention has been described in detail by

specific reference to preferred embodiments, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.